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EXPLOITATION AND UTILIZATION OF OIL SHALE IN THE COAL MEASURE STRATA OF THE HAISHIWAN MINE, YAOJIE COALFIELD, CHINA

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Abstract. *Oil shale, a kind of energy source, is an important alternative to petroleum. Considering the Haishiwan mine of the Yaojie coalfield, China, as a typical study case, an exploitation and utilization system for oil shale was investigated. The system consists of oil shale mining and comprehensive utilization. Haishiwan oil shale has developed in a paragenetic relationship with humic coal in coal measure strata. Underground mining technology is applied to the oil shale seam. The exploitation and utilization system for Haishiwan oil shale has a great significance for two reasons. On the one hand, combined with gas drainage technology, the mining of the oil shale seam can eliminate the risk of coal and gas outburst from the underlying coal seam in a particular area and ensure the safe mining of the coal seam. Thus the economic value of this thin oil shale seam is improved. On the other hand, the mined oil shale can be fully made use of by a comprehensive utilization technology. The latter includes oil shale retorting, combustion of semicoke, fine oil shale and fuel gases for power generation, and utilization of ashes for production of composite cement and other building materials. The industrial chain for oil shale exploitation and utilization established in the Yaojie coalfield is highly significant for maximizing the utility of resources and reducing environmental pollution.*

Keywords: *exploitation and utilization, Haishiwan oil shale, coal measure strata, oil shale mining, oil shale retorting.*

1. Introduction

In 2012, the total world energy consumption was 8979 Mtoe (million tons of oil equivalent). Approximately 66.0% of this energy was provided by fossil fuels (coal, natural gas and oil), oil accounting for the major part of it

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(approximately 40.7%) [1]. Oil will remain the worldwide dominating energy source also in the future [2]. In 2013, the total primary energy consumption in China was 2852.4 Mtoe. China's share of the total world energy consumption was approximately 22.4%, being the largest in the world [3]. China depends strongly on conventional energy, and the supply-demand situation concerning several energy sources, notably crude oil, is increasingly tense [4]. For example, in 2012, the country produced and consumed 295.445 Mtce (million tons of coal equivalent) and 678.777 Mtce of oil, respectively [5]. In China, the total oil shale resources are estimated at 7199.37×10^8 t (when converted to shale oil, approximately 476.44×10^8 t) [6]. Oil shale as an energy source is an important alternative to crude oil [7, 8]. If oil shale resources are adequately exploited, then domestic oil energy demand pressures will be effectively relieved.

Only four countries (China, Estonia, Brazil and Australia) produce shale oil by oil shale retorting technology and by the end of 2013, their total annual output was approximately 140×10^4 t [9]. Shale oil can be produced by surface retorting technology and in-situ technology [10]. At present, in-situ technology is still in the development stage, while surface retorting technology is the main way to obtain oil from oil shale. Some countries such as Estonia, China, Canada, the USA and Brazil have developed different oil shale retorting technologies [11]. They include Paraho technology (USA) [11], Fushun-type technology (China) [12, 13], Kiviter and Galoter technologies (Estonia) [14, 15], Petrosix technology (Brazil) [16] and ATP technology (Canada) [17].

Additionally, oil shale also has a wide range of applications in other fields such as construction industry and agriculture [18–20]. To achieve the goal of energy conservation and environmental protection, some specialists proposed a comprehensive utilization technology for oil shale [21–24]. Firstly, oil shale is transported into a retort furnace to produce shale oil, semicoke and retorting gas. Secondly, semicoke and fine oil shale are burned in the circulating fluidized bed (CFB) furnace to generate electricity. Estonia has carried out many industrial-scale oil shale combustion experiments using different technologies. Compared to the more traditional pulverized firing (PF) furnace, the CFB furnace has several advantages such as satisfactory combustion efficiency, relatively low pollutant emissions and better adaptability [25–31]. CFB technology has been so far the most popular combustion method [22, 28]. Thirdly, CFB ashes have promising utilization prospects. These ashes can be used in producing building materials such as cement and ceramsite [32, 33], precipitated calcium carbonate (PCC) [34, 35], glass ceramics [36, 37], adsorbents and other high valued-added chemical products [38, 39].

In case of surface retorting, oil shale needs first to be transported to the surface by open pit or underground mining. Both these techniques are employed in Estonia and China [40, 41]. In many mining areas of China, such as the Fushun Basin in Liaoning Province and the Huangxian Basin in

Shandong Province, coal and oil shale exist together in the same sedimentary strata [7, 42]. In these types of basins, coal and oil shale seams mining activities inevitably influence each other, especially when the underground mining method is used. At present, attention is mostly focused on oil shale utilization, while there are few reports on the above-mentioned aspect.

Coal and oil shale are paragenetic in the Haishiwan mine of the Yaojie coalfield. At the same time, the underlying coal seam involves a high coal and gas outburst risk. Mining directly this type of coal seam would easily result in dynamic disaster, which will cause not only casualties but also economic loss [43, 44]. Protective seam exploitation technology is so far a safer and more effective method for weakening and even eliminating the outburst risk of the coal seam (called protected seam) [45, 46]. In the Haishiwan mine, the oil shale seam is selected as a protective seam (also called first-mined seam). Combined with coal seam gas drainage technology, the mining of Haishiwan oil shale can eliminate the outburst risk of the coal seam. Hence, the mining of this oil shale seam contributes to the safe production in the Haishiwan mine. In the past few years, large amounts of oil shale have been transported to the surface and piled up in the minefield. Therefore, not only the surrounding field was contaminated but also these resources were wasted, and even their spontaneous combustion may take place. For solving these problems, the industrial projects on oil shale comprehensive utilization including oil shale retorting, combustion of semicoke, fine oil shale and fuel gases for power generation, and ashes utilization are being implemented. To the mined oil shale a comprehensive utilization technology can be applied. Hence, taking into account the specific conditions in the Haishiwan mine, an exploitation and comprehensive utilization system for oil shale is proposed in this paper. The system is significant for the sustainable development of the Yaojie coalfield.

2. Geological setting

The Minhe Basin is a mountain depression basin that developed in the Mid-Qilian massif during the Mesozoic and Cenozoic. The basin extends across Gansu and Qinghai provinces. As shown in Figure 1, the Yaojie coalfield is located in the western part of the basin and is occupied by the Jinhe and Haishiwan mines. The Minhe Basin is divided into four first-level tectonic units [47], and the Haishiwan mine lies south of the Zhoujiatai fault uplift. The F19 fault verges on the Haishiwan mine. This fault of long-term development and multi-stage activity has had a great influence on the formation and later development of the coal measure strata in the Yaojie coalfield [48, 49].

As shown in Figure 2, the Yaojie Formation in the Haishiwan mine consists of five members. Three types of oil shale exist in the formation: the

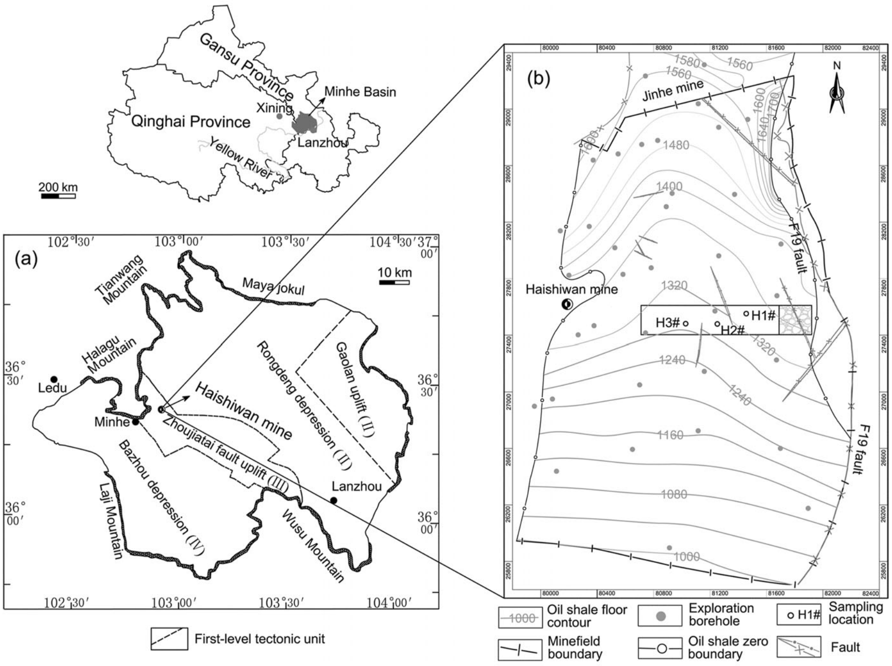

Fig. 1. (a) Simplified tectonic map of the Minhe Basin [47]; (b) geological map of the Haishiwan mine showing the distribution of oil shale in the coal measure strata.

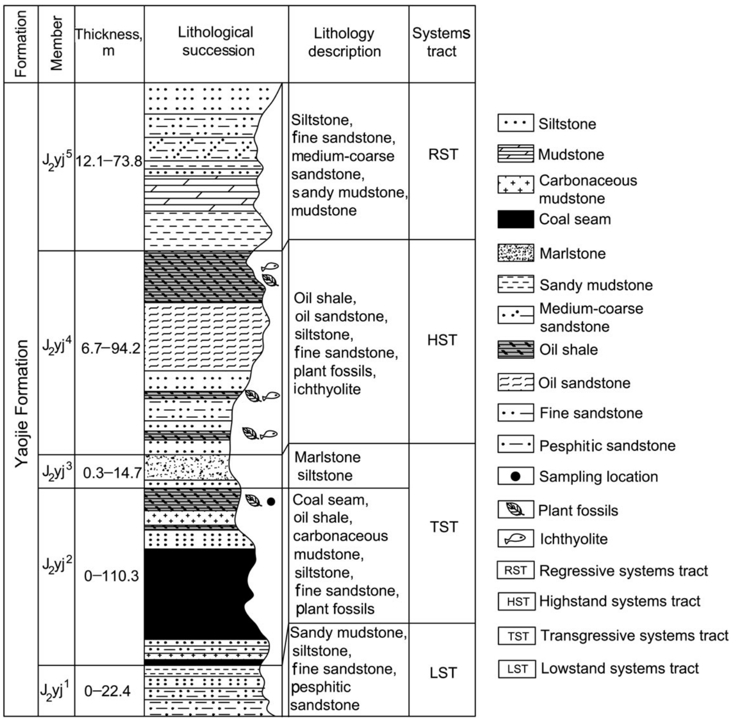

Fig. 2. Stratigraphic columns for the Yaojie Formation in the Haishiwan mine.

sapropelic type of deep-lacustrine facies, the humosapropelic type of shallow lake facies and the sapropelic-humic type of lacustrine swamp facies [50, 51]. During the transgressive systems tract (TST) stage, sapropelic-humic oil shale (with a maximum thickness of 11.79 m and an average thickness of 4.14 m) developed in a paragenetic relationship with humic coal in the coal measure strata of the second member (J_2yj^2) stratum. The sapropelic-humic oil shale floor contour is shown in Figure 1. The burial depth distribution of this oil shale in the Haishiwan mine shows its seam depth in the north to be shallower than in the south. Nowadays, in view of its higher quality, only the sapropelic-humic oil shale seam is being exploited by underground mining technology.

3. Characteristics of Haishiwan oil shale

3.1. Basic properties

For the study, three oil shale samples were collected from a working face of the Haishiwan mine (Fig. 1). The samples had a dim grey black color, compact massive structure, hard texture and smooth fracture (Fig. 3a). The surface morphology of samples determined by a scanning electron microscope (SEM) is shown in Figure 3b. The figure shows that Haishiwan oil shale has an irregular and coarse surface on which several bright and massive minerals reside. Additionally, the numerous different sized pores are distributed in a honeycomb shape, showing that the oil shale has a well-developed micropore structure.

The results of geochemical and petrographic analyses of Haishiwan oil shale samples are presented in Table 1, the results of ultimate analysis of the samples are given in Table 2.

The sapropelinite group has a maximum generation potential compared to other organic macerals [7], with the volume content of 59.0% in Haishiwan

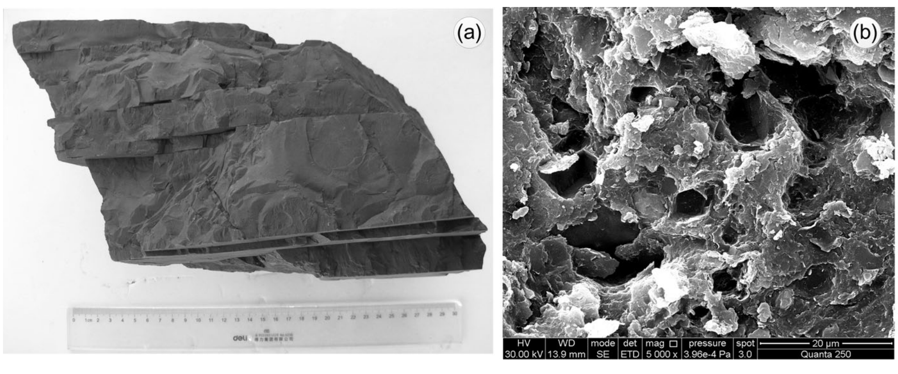

Fig. 3. (a) Photograph of oil shale (H1#); (b) surface micro-structure morphology of oil shale (H1#, SEM 5000×) from a cleaned and dried sample from a polished section using a coating film.

Table 1. Geochemical and petrographic analyses of Haishiwan oil shale samples

Sample no.	Proximate analysis, wt%				TD, g/cm^3	TOC, wt%	Maceral, vol%				$R_{o,\ max}$, %
	Mois	Ash	VM	FC			S	V	I	M	
H1#	1.32	42.36	57.33	24.04	1.64	38.6	–	–	–	–	–
H2#	0.82	48.12	75.84	12.34	1.82	31.2	–	–	–	–	–
H3#	1.31	53.58	58.84	18.52	1.85	27.8	59.0	12.6	7.4	21.0	0.635
Average	1.15	48.02	64.0	18.30	1.77	32.5					

Note: Mois – moisture; Ash is on air-dry basis; VM – volatile matter, on dry ash-free (daf) basis; FC – fixed carbon, on air-dry basis; TD – true density; TOC – total organic carbon; S – sapropelinite group; V – vitrinite; I – inertinite; M – mineral; $R_{o,\ max}$ – mean maximum vitrinite reflectance.

Table 2. Results of ultimate analysis of Haishiwan oil shale samples

Sample no.	Ultimate analysis, %			
	C_{ad}	H_{ad}	N_{ad}	S_{ad}
H1#	44.17	4.27	1.14	1.22
H2#	35.38	3.66	0.72	1.10
H3#	32.67	3.05	0.91	1.50

Note: $_{ad}$ – on air-dry basis.

oil shale. It has been established before that TOC content of oil shale has a positive effect on oil yield [52]. Compared with TOC contents of oil shales from the other ten oil shale-bearing areas in China [7], Haishiwan oil shale's TOC content is relatively high, with an average of 32.5%. Additionally, the oil shale is in an immature-low mature stage because of its low metamorphic grade ($R_{o,\ max}$ 0.635%).

3.2. Pyrolysis characteristics

The pyrolysis characteristics of Haishiwan oil shale have been studied previously [53]. In that study, a new type of retort (called the SJ-type pilot-scale retort) was employed. Table 3 presents the Fischer assay results for Haishiwan oil shale. The oil shale samples have a high oil content, between 4.11% and 18.42%, with an average content of 10.86%, the yields of semicoke and retorting gas are on average 83.63% and 3.62%, respectively.

Table 3. Fischer assay results for Haishiwan oil shale, air received basis, ar%

Sample	Shale oil	Water	Semicoke	Gas
Haishiwan oil shale	4.11 – 18.42 10.86(9)	1.19 – 2.55 1.89(9)	74.80 – 92.63 83.63(9)	2.01 – 5.01 3.62(9)

Note: above the line – range of data; below the line – average; in the brackets – number of samples.

The yields of shale oil, semicoke, retorting gas and water produced from Haishiwan oil shale at the pyrolysis temperatures from 450 °C to 530 °C are shown in Figure 4. The organic matter of oil shale, named kerogen, is gradually pyrolyzed with increasing temperature, which results in a decrease of semicoke and increase of both the retorting gas and shale oil. As the temperature increases from 450 °C to 510 °C, the retorting gas yield increases slowly from 3.15% to 4.34%; meanwhile, the oil yield increases relatively rapidly from 6.53% to 8.29%. However, when the pyrolysis temperature increases from 510 °C to 530 °C, the oil yield increases by only 0.05% and that of the retorting gas rises from 4.34% to 5.55%.

The weight ratio of retorting gas to shale oil decreases from 2.073 at 450 °C to 1.503 at 530 °C. This indicates that the increased rate of retorting gas yield is higher than that of shale oil yield with increasing temperature. The shale oil yield does not change significantly when the temperature is above 510 °C, likely because more organic matter is directly converted into retorting gas. In addition, some gas is produced from desorption of adsorbed gas on the surface and in the micropores of oil shale and from the decarboxylation and decomposition of carbonate and organic compounds [54]. Other studies [55, 56] noted that a maximum shale oil yield can be obtained at a specific temperature called the optimum. When the temperature exceeds the optimum, the shale oil yield may decrease due to the aggravation of secondary pyrogenation reactions and the cracking reaction of shale oil, producing an increase in retorting gas [57, 58]. The maximal oil yield of Huadian oil shale was obtained at a temperature of 530 °C [59]. The

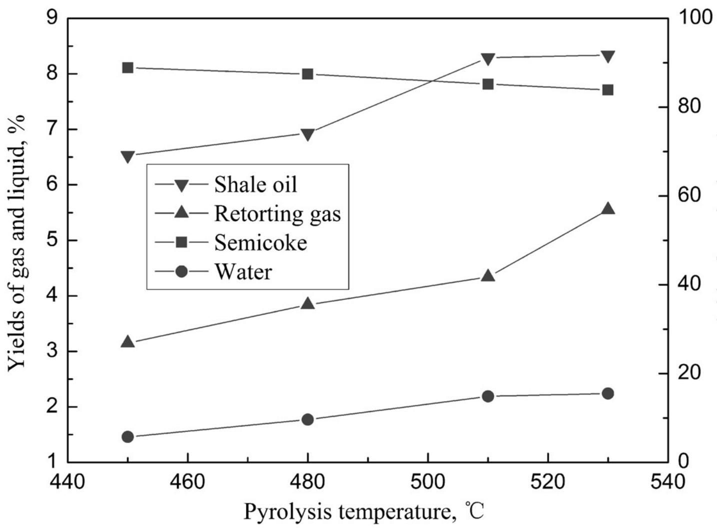

Fig. 4. Pyrolysates yields from Haishiwan oil shale at different pyrolysis temperatures.

maximum total yield of thermobitumen (TB) and oil from kerogen of Estonian kukersite oil shale was obtained at a nominal temperature of 410 °C after a 40-minute processing [60]. Therefore, the retorting temperature of 510–530 °C is likely the optimum and the temperature at which a maximal oil yield was previously obtained was near 525 °C [61]. Hence, for Haishiwan oil shale the retorting temperature of 510–530 °C is recommended as the optimum.

3.3. Pyrolysis product properties

Upon heating, kerogen is converted into final pyrolysis products, including shale oil, semicoke and retorting gas.

The retorting gas is a compound gas containing nitrogen, carbon dioxide, hydrogen, several alkanes and various alkenes (Table 4). The calorific value of the gas mixture is 5145.83 kJ/m^3. The calorific value of the shale semicoke is 4274 kJ/kg (Table 5). The shale oil properties are listed in Table 6. The distillation range of shale oil is 149.6–588.6 °C. For shale oil distillation, the content of the gasoline fraction, diesel fraction and heavy oil fraction is 2.5 wt%, 48.1 wt% and 49.4 wt%, respectively.

Table 4. Composition of the retorting gas

Gas component	Percentage, vol%	Gas component	Percentage, vol%
Nitrogen	63.061	n-Butane	0.054
Carbon monoxide	8.646	iso-Butane	0.05
Carbon dioxide	9.61	n-Pentane	0.021
Hydrogen	14.061	Ethylene	0.508
Methane	3.478	Propylene	0.028
Ethane	0.301	1-Butene	0.013
Propane	0.042	Acetylene	0.127

Table 5. Properties of oil shale semicoke

Sample	Proximate analysis, %				Calorific value, kJ/kg
	Moisture	Ash	Volatile matter	Fixed carbon	
Semicoke	3.90	84.79	4.10	7.21	4274

Table 6. Results of analysis of the properties of shale oil

Parameter		Result
Moisture, %		0.76
Ash, %, $\times 10^{-2}$		0.769
Sulfur, %		0.521
Carbon residue, %		1.20
Mechanical impurity, %		0.037
Density, kg/m^3		913.6
Kinematic viscosity, 50 °C, mm^2/s		10.514
Solidification point, °C		24
Distillation range, °C	Initial boiling point	149.6
	Final boiling point	588.6
Fractional distribution, wt%	Gasoline fraction	2.5
	Diesel fraction	48.1
	Heavy oil fraction	49.4
Asphalt fraction, %	Saturated hydrocarbons	47.94
	Aromatic hydrocarbons	22.36
	Resin	26.38
	Asphaltene	3.33

4. Exploitation and utilization system

4.1. System description

As shown in Figure 5, the exploitation and utilization system for Haishiwan oil shale includes oil shale mining and comprehensive utilization. Underground mining technology is applied to oil shale and coal seams because the coal measure strata have a great burial depth. However, mining only the oil shale seam is not beneficial because of its small thickness. The mining value of oil shale mainly reflects two aspects. First, the mining of Haishiwan oil shale seam as a protective seam can prevent and control coal seam gas disasters, ensuring the safety of mining of the underlying coal seam. Second, several high economic value products, such as shale oil, can be obtained by employing the comprehensive utilization technology for oil shale.

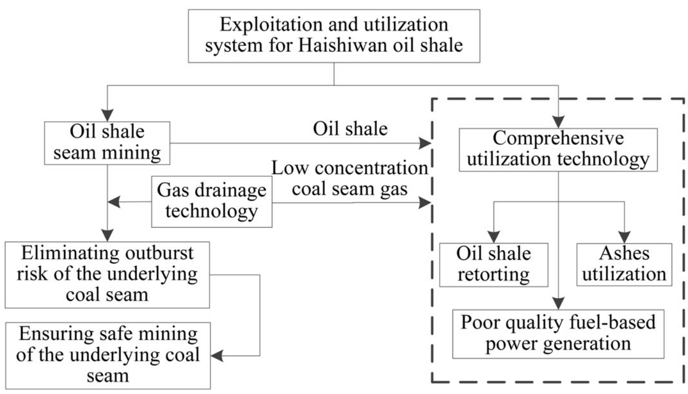

Fig. 5. Exploitation and utilization system for Haishiwan oil shale.

In the Haishiwan mine, the underlying coal seam, which is a low metamorphic and high volatility bitumite, has a high mining value due to its average thickness of approximately 30 m. However, this coal seam has a serious coal and gas outburst risk (gas pressure 1.0–7.5 MPa, gas content 44.7 m^3/t). Additionally, the permeability of the seam is low. Therefore, the gas control technology pattern [62, 63], which is the combination of the protective seam exploitation technology and the stress-relief gas drainage method, is applied to prevent and control the outburst risk of coal seams with high methane contents. When the Haishiwan oil shale seam (the protective seam) with no outburst risk (gas content 2–3 m^3/t) is mined first, the phenomena of floor heave and floor deformation occur in the goaf, which will move the rock stratum, develop fractures and increase the penetrability in the underlying stratum [64]. Therefore, these initial mines can form a favorable environment, advancing gas desorption, diffusion and seepage in the coal seam. Additionally, when combined with stress-relief gas drainage technology, the gas content in the coal seam will decrease greatly. Hence, the outburst risk area of the coal seam will turn into the non-outburst risk area.

As shown in Figure 6, Haishiwan oil shale is utilized by the comprehensive utilization technology. This technology includes oil shale retorting,

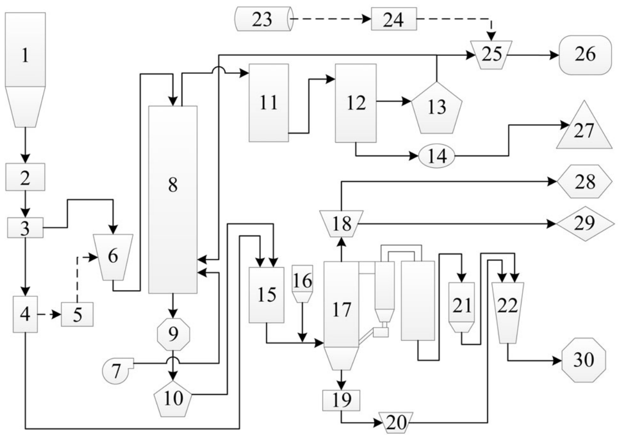

Fig. 6. Schematic diagram of the comprehensive utilization technology for Haishiwan oil shale (modified after [23, 65]): 1 – oil shale bunker; 2 – roller pulverizer; 3 – vibrating screen; 4 – fine material hopper; 5 – oil shale balls forming machine; 6 – coarse material hopper; 7 – centrifugal fan; 8 – SJ-type retort; 9 – cooling device; 10 – semicoke bunker; 11 – venturi primary cooling tower; 12 – final cooling tower; 13 – electrostatic decoking device; 14 – oil-water separator; 15 – mixture hopper; 16 – limestone hopper; 17 – circulating fluidized bed boiler; 18 – steam turbine; 19 – cooler; 20 – slag hopper; 21 – precipitator; 22 – ash bunker; 23 – low concentration coal seam gas; 24 – CO_2 purification device; 25 – gas-mixing equipment; 26 – gas turbine generator set; 27 – shale oil tank; 28 – heat exchanger; 29 – electricity generator; 30 –ashes utilization factory; (connected by dashed lines – items of ongoing researches).

poor quality fuel combustion for power generation and ashes utilization. First, coarse oil shale particles (8–60 mm) are transported into the SJ-type furnace to produce shale oil, oil shale semicoke and retorting gas. Second, the shale oil is stored in storage tanks. The semicoke and fine oil shale particles (0–8 mm) are fed into the CFB furnace to generate electricity and heat, and the retorting gas is fed into the gas turbine to generate electricity. Finally, the ashes from the CFB furnace are transported to an ashes utilization factory to produce composite cement and other building materials.

4.2. Oil shale seam mining

The identical minefield development and underground ventilation systems are applied to oil shale and coal seams in the Haishiwan mine. A fully-mechanized full-seam mining technology is used because of the small thickness of the oil shale seam. Additionally, the retreating longwall method is employed for the working face, and the roof is managed by the full caving method.

To study the stress relief effect of the underlying coal seam, the numerical software FLAC^{3D} was used to analyze the vertical stress distribution of the coal seam in the case of mining the oil shale seam. As shown in Figure 7, based on the geological conditions of the Haishiwan mine, a model with dimensions of 500 m × 400 m × 200 m was constructed. The bottom boundary in the vertical direction (Z) and the boundary in the horizontal directions (X and Y) were fixed. To simulate the overburden load of 450 m, a uniformly distributed load of 10 MPa was exerted over the model. The elastic-plastic constitutive Mohr-Coulomb model and the Null model were selected for the simulation.

As shown in Figure 8, when the advance distance of the oil shale seam working face is 200 m, the de-stress effect occurs in the underlying coal seam. The vertical stress of both the roof and the floor of the underlying coal

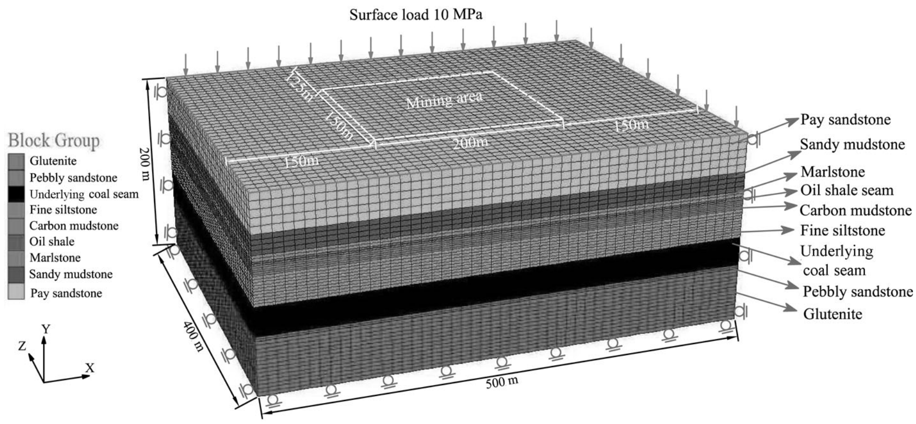

Fig. 7. Numerical simulation model of FLAC^{3D}.

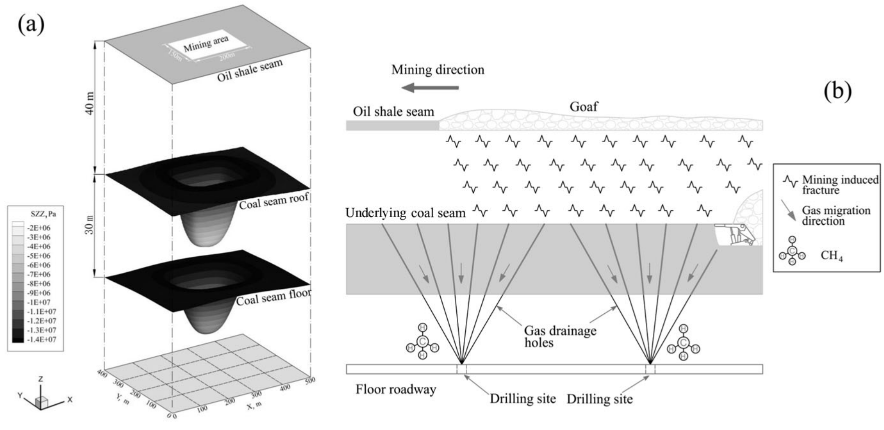

Fig. 8. (a) The distribution of vertical stress after mining the oil shale seam; (b) the diagram of oil shale mining and stress-relief gases drainage.

seam displays a minimum stress of –1.47 MPa and –3.90 MPa and reduces by 11.28 MPa and 9.6 MPa compared with their initial stress, respectively. After the oil shale is mined, the underlying stratum exhibits a significant de-stress effect. A lot of mining-induced fractures develop, which favour the migration of stress-relief gases in the coal seam. Therefore, those stress-relief gases can be easily and efficiently extracted from the coal seam by the gas drainage technology. The gas control technology not only reduces the coal seam gas content and eliminates the outburst risk of the high gas coal seam, but also ensures the safe mining of coal and oil shale seams.

4.3. Comprehensive utilization technology

4.3.1. Oil shale retorting

A schematic diagram of the retorting technology for Haishiwan oil shale is shown in Figure 9. The oil shale retorting system can be divided into four sections: the oil shale material preparation section, the oil shale retorting section, the retorting gas purification section, and the semicoke storage section. In the process of oil shale preparation, Haishiwan oil shale is transported directly from the working face to industrial sites by belt conveyors. Applying working procedures, which include impurity removal, crushing and sieving, coarse (particle size 8–60 mm) and fine (particle size 0–8 mm) oil shale are obtained. The former is the retorting material and the latter is mainly burnt for power generation.

At present, the Fushun retort furnace or its modified version is widely applied in the oil shale processing industry in China [66]. By contrast, the SJ-IV rectangular furnace employed in the Yaojie coalfield has several advantages such as higher oil yields, larger daily capacities (the design capacity is 500 t/d) and lower calorific value loss of semicoke [67]. In the

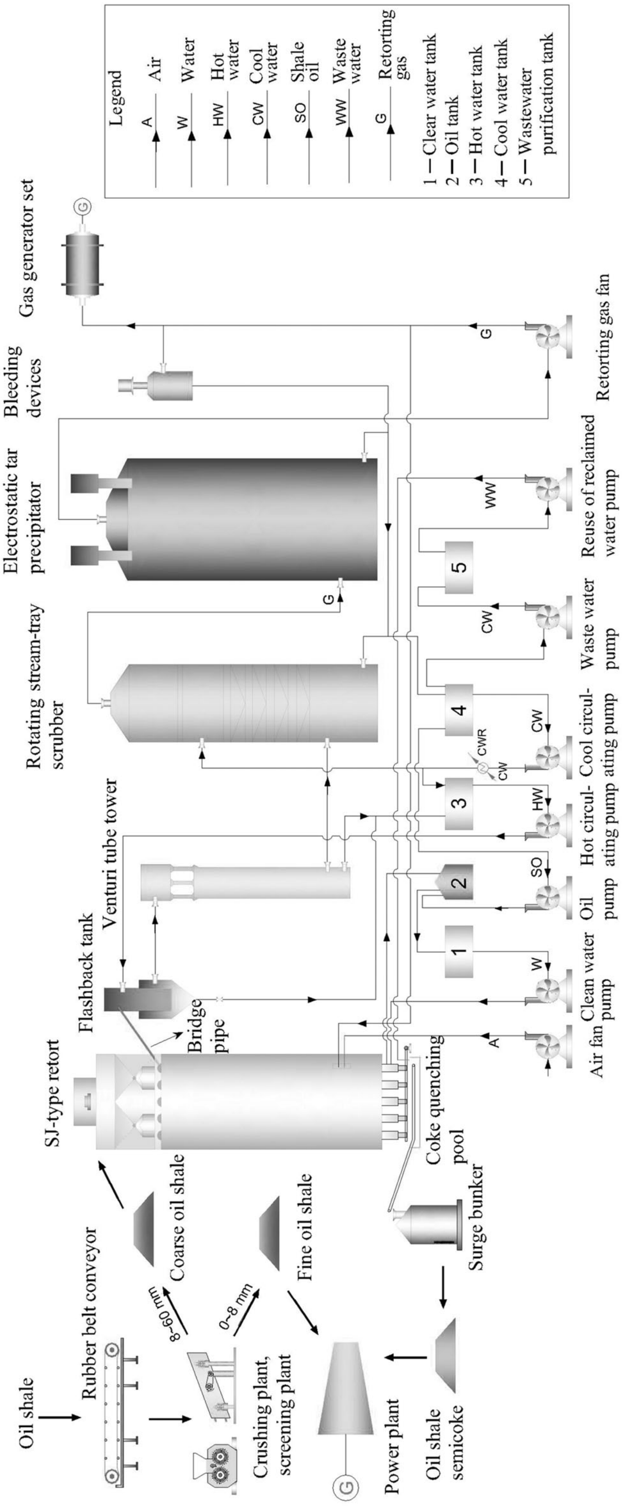

Fig. 9. Schematic diagram of the retorting technology for Haishiwan oil shale.

SJ-type furnace, free-falling coarse oil shale (8–60 mm) undergoes three different physical-chemical processes: the drying phase, the retorting phase and the cooling phase. In the drying phase, the water and adsorbed gas in coarse oil shale are evaporated in the elevated temperature fuel gas environment. In the retorting phase, oil shale reacts to produce shale oil, fuel gas and semicoke. When falling into the pyrolysis zone, oil shale is heated. The pyrolysis zone temperature is 550–700 °C. In the cooling phase, after cooling to approximately 80 °C in a coke quenching pool, semicoke is transported to a surge bunker.

After passing through the three-level purification equipment, some amount of retorting gas is sent to the furnace and fired to provide the required heat for oil shale pyrolysis. The residual gas is burned for power generation in the fuel gas turbine-equipped power plant.

When crude oil shale is crushed, large amounts of fine oil shale (0–8 mm) are produced. Fine oil shale is fed directly into the furnace, which may cause an uneven temperature distribution and lead to the incomplete pyrolysis of oil shale. A previous study [61] investigated the retorting of Haishiwan oil shale balls (29 mm × 38 mm) made of fine oil shale, bentonite and water. The results showed that when the mass proportions of fine oil shale, bentonite and water were 86.5%, 7.5% and 6%, respectively, oil and gas yields were less affected (Table 7). Therefore, if such fine oil shale can be fed into the furnace successfully, then the required retorting material and stable oil yield can be ensured.

Table 7. Fisher assay results for coarse oil shale particles and oil shale balls (after [61])

Sample	Oil, %	Water, %	Gas, %
Coarse oil shale particles	12.23	2.84	3.74
Oil shale balls	12.06	2.94	3.85

4.3.2. Power generation

The power generation system can be divided into two parts: combustion of fuel gases for power generation and co-combustion of semicoke and fine oil shale for power generation.

At present, the fuel gas used for generating electricity is mainly retorting gas. A substantial amount of low concentration gas is extracted from the underlying coal seam using the stress-relief gas drainage technology. In the Haishiwan mine, the extracted gas amount is approximately 5990 m^3/h. In the gas extraction pipeline, the gases consist mainly of N_2, CO_2 and CH_4 with a volume fraction of 22.74%, 54.46% and 20.61%, respectively. Regardless of the amount of the retorting gas burnt in the furnace, the residual gas amount is ca 48000 m^3/h. To fully utilize the two fuel gases, the gases are blended at a ratio of about 1 to 8 (5990:48000). The components of the gas mixture are given in Table 8.

Table 8. Components of the gas mixture

Gas component	Percentage, vol%	Gas component	Percentage, vol%
Nitrogen	58.581	n-Butane	0.048
Carbon monoxide	7.685	iso-Butane	0.044
Carbon dioxide	14.593	n-Pentane	0.019
Hydrogen	12.499	Ethylene	0.452
Methane	5.382	Propylene	0.025
Ethane	0.268	1-Butene	0.012
Propane	0.037	Acetylene	0.113

The calorific value of the gas mixture is 5942.05 kJ/m^3. A previous study [68] indicated that mixed gases comprised of low concentration coal seam gas and retorting gas are better materials for power generation in terms of combustion control. The fuel gases co-combustion based power generation system not only fully utilizes coal seam gas, but is also more conducive to control the operation of the gas internal combustion engine generating set due to decreasing the hydrogen content in the cylinder.

Poor quality fuels such as semicoke, fine oil shale and coal gangue, with some coal from the underlying coal seam, can be fed into the CFB furnace to generate electricity and heat. To reduce SO_2 emissions, a limestone in-furnace desulphurization system is added. Additionally, the ashes from both oil shale and coal contain minerals such as CaO, MgO and Fe_2O_3 (Table 9). Therefore, the desulphurization reaction between these minerals and SO_2 will occur during the combustion of the fuel.

CFB furnace (the furnace temperature less than 1000 °C) combustion is a low temperature combustion technology. Therefore, CFB furnace ashes are distinct from PF furnace ashes in their physicochemical properties and phase compositions because of the lack of high temperate sintering [31, 69]. Substantial amounts of oil shale ashes produced in the CFB furnace have wide utilization prospects. In the Yaojie coalfield, some amount of ashes is transported to a cement grinding station to produce cement, baking-free bricks and other building materials and the remainder is delivered to customers.

Table 9. Components of oil shale ash and coal ash, wt%

Sample \ Component	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	TiO_2
Oil shale ash	64.50	19.46	8.73	1.26	1.48	0.14	1.36	0.55	1.37
Coal ash	40.96	19.77	8.87	15.1	7.94	2.67	0.61	0.59	1.05

5. Exploitation and utilization prospects

Currently, the oil shale comprehensive utilization technology used in the Yaojie coalfield enables production of shale oil, electricity, heat, as well as construction materials like composite cement and baking-free bricks (Table 10).

Table 10. Current status of oil shale comprehensive utilization in the Yaojie coalfield

Item	Production capacity
Shale oil	11×10^4 t
Fuel gases combustion for power generation (first-stage project)	7.5 MW[a]
Semicoke and fine oil shale co-combustion for power generation	7×10^8 kWh
Composite cement	60×10^4 t
Baking-free brick	6.0×10^7 pcs
Fine oil shale (0–8 mm) retorting*	–
Low concentration coal seam gas and retorting gas co-combustion for power generation* (second-stage project)	10.5 MW[b]

Note: * – project item in progress; [a,b] – installed capacity.

The oil shale retort system requires approximately 125×10^4 t of coarse oil shale (8–60 mm) annually. Most of the oil shale comes from the Haishiwan mine, and the remainder is provided by the neighboring Jinhe mine (oil content 15.11% [53]). To achieve high economic benefits, the oil shale utilization system employed in the Yaojie coalfield should be constantly optimized. Two challenges need to be addressed: (1) ensuring the supply of oil shale with sufficient oil content; and (2) taking full advantage of coal seam gas from the underlying coal seam.

Currently, the projects that use fine oil shale retorting, and low concentration and retorting gases co-combustion for power generation are being implemented in the Yaojie coalfield. These projects can handle the above two problems and, in addition, also reduce CH_4 emissions. China's annual output of shale oil is approximately 70×10^4 t [9]. Shale oil is an unconventional oil resource and has broad exploitation prospects in China. Several high value-added fine chemicals can be extracted from shale oil by using separation and refinement technologies [70, 71]. Therefore, projects investigating shale oil processing should be considered and implemented to reduce the influence of oil prices on shale oil exploitation. Continuing scientific research, maximizing resources utility and enhancing the management level are all important approaches to improve the economic and social efficiency of the Yaojie coalfield.

6. Conclusions

In the Haishwian mine, the sapropelic-humic oil shale has developed in a paragenetic relationship with humic coal in the second member (J_2yj^2) stratum. The oil shale deposit has a great burial depth and a small layer thickness. The mining of the oil shale seam would contribute to the safe mining of the underlying coal seam. The mined oil shale can be exploited more fully by a comprehensive utilization technology. The oil shale exploitation and utilization system proposed in this paper for Haishiwan oil shale consists of oil shale mining, oil shale retorting, poor quality fuel-based power generation, and ashes utilization. The main conclusions can be summarized as follows:

(1) Haishiwan oil shale has a high organic matter content and oil yield, 32.5% and 10.86%, respectively. A temperature of 510–530 °C is recommended as the optimum for retorting the oil shale.
(2) To the oil shale seam a fully-mechanized full-seam underground mining technology can be applied. Numerical simulation results show that the vertical stress of the underlying coal seam decreased significantly after the oil shale had been mined. Because of this de-stress effect, plenty of mining-induced fractures develop, which contribute to the migration of stress-relief gases in the coal seam. And, combined with gas drainage technology, the risk of coal and gas outburst from the underlying coal seam can be eliminated.
(3) The exploitation and utilization system for Haishiwan oil shale has significance from two aspects. First, the mining of the oil shale seam can effectively control coal and gas dynamic disaster and thus improve the economic value of this thin oil shale seam. Second, Haishiwan oil shale can be fully utilized by the comprehensive utilization technology that enables production of several valuable products. The proposed system can take full advantage of the oil shale and coal seam gas resource, which contributes to the sustainable development of the Yaojie coalfield.

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