Lithotype and Coal Quality Characteristics and Clean Utilization Direction of Badaowan Formation Coal Seam 4-2 in Panji Coal Mine, Xinjiang

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Abstract. Turpan-Hami Basin contains abundant coal resources and is an important part of large coal base in Xinjiang. In this study, the 4-2 coal seam of the Badaowan Formation in the Lower Jurassic in the Panji Coal Mine in the Turpan-Hami Basin is selected as the research object. Through systematic analysis of maceral, maximum reflectance of vitrinite, ash, volatile, sulfur, hydrogen carbon atomic ratio, chlorine, fluorine and arsenic elements in coal, combined with the evaluation index system of coal cleanliness grade and direct coal liquefaction, the clean potential and clean utilization method of the 4-2 coal seam are investigated. The 4-2 coal seam of Panji Coal Mine has the characteristics of relatively low chlorine and arsenic contents and relatively high ash, sulfur and fluorine contents. The high ash content is the main obstacle to the clean utilization of coal in Panji Coal Mine. The research results show that clean coal grade is of category III for raw coal, belonging to relatively unclean coal. The coal types of 4-2 coal seam are mainly composed of brown coal, long-flame coal, and non-caking coa, with relatively low inertinite content, extremely low-low ash, high volatile content and high hydrogen-carbon atom ratio. Floating coal meets the evaluation criteria for direct liquefaction coal and is suitable for use as class II direct liquefaction coal. The research results have important guiding significance for the clean and efficient utilization of coal resources in Panji Coal Mine.

Keywords: Panji Coal Mine; Baodawan Formation; coal petrology and coal quality; clean utilization; direct liquefaction.

1 Introduction

The energy structure has long been dominated by coal, and coal will remain the main energy source in the energy supply system for the current and the next relatively long period in China [1,2]. Based on our basic national energy situation of "lack of oil, less gas, relatively rich in coal", the clean and efficient utilization of coal has become the inevitable choice under the current circumstances [3]. Coal direct liquefaction, as an

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important means of clean and efficient utilization, has significant implications for reducing environmental pollution, improving energy utilization efficiency, and ensuring national energy security [4].

The Turpan-Hami Basin (THB: collectively referred to as the Turpan Depression and the Hami Depression) is rich in coal resources and has broad prospects for development and utilization. It is an important coal resource base in Xinjiang [5-8]. With the development of technology and the support of policies, the coal resources in the Turpan-Hami Basin have ushered in new development opportunities and will develop in a more clean and efficient utilization direction. In this study, the 4-2 coal seam of the Badaowan Formation in the Lower Jurassic in the Panji Coal Mine in the THB is selected as the research object. Through systematic analysis of coal petrology, coal quality, and harmful elements in coal, the clean utilization direction of the 4-2 coal seam is evaluated, which has guiding significance for realizing the classified and graded utilization and clean and efficient utilization of coal resources in the Panji Coal Mine.

2 Geological Setting

The Panji Coal Mine is located in the low hilly area on the northwest fringes of the Turpan Basin. A vast majority of the surface is blanketed by the alluvial and proluvial layers from the Late Pleistocene, while the Mesozoic strata are intermittently exposed. The landscape is dominated by rock deserts and gravel deserts. The highest point reaches roughly 1420 meters (in the northwest) and the lowest is approximately 1000 meters (in the southeast). Generally, the terrain in this region slopes downward from the northwest to the southeast, with the ground slope spanning from 25° to 50°(Fig. 1).

The strata evolving in the study area include the Paleozoic Silurian, Carboniferous, and Permian strata, which constitute the basement of the inter-mountain depression in the study area. On this basement, the Mesozoic Triassic, Jurassic strata, as well as the Cenozoic Tertiary and Quaternary strata have been deposited(Fig. 1). Among them, the Badaowan Formation of the Lower Jurassic is the main coal-bearing stratum in this area. The average thickness of this group of strata ranges from 307m to 480m, and the strata gradually thicken from east to west. The Badaowan Formation was formed through fluvial facies, lacustrine facies, and peat swamp facies. The lithology comprises taupe, gray-green conglomerate, glutenite, sandstone, along with gray-green, gray, and gray-black siltstone, mudstone, and coal seams. There are 14 sets of coal seams developed within the Badaowan Formation. Among them, the 4-2 coal seam is situated in the upper portion of the Badaowan Formation. The structure of this coal seam is straightforward and its thickness remains relatively stable along the strike, falling into the category of coal seams that can be mined across the entire area. The thickness of the 4-2 coal seam varies between 0.99m and 4.26m, with an average thickness of 2.99m.

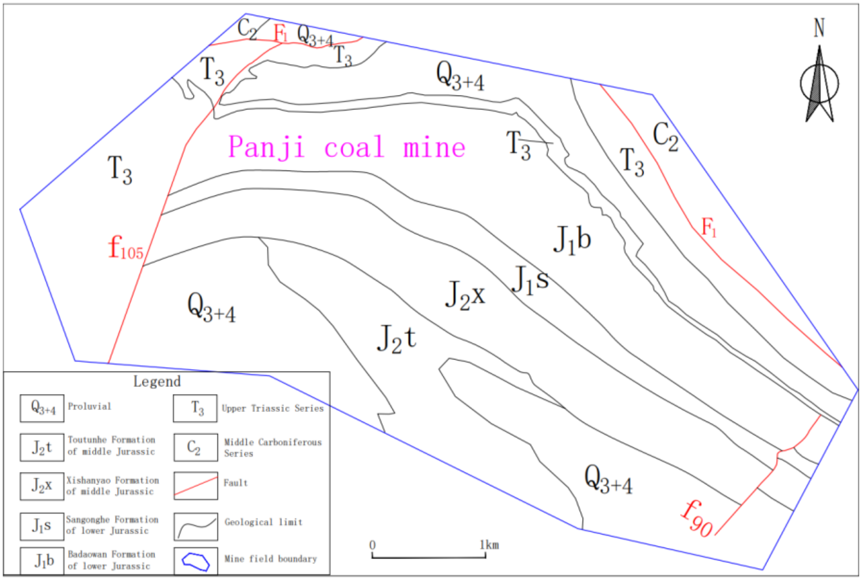

Fig. 1. Regional geological map of Panji coal mine.

3 Lithotype and Coal Quality

3.1 Lithotype

The No. 4-2 coals appear black, mainly in the form of lumps and powders. The macroscopic lithotypes are mainly semi-dull coal, followed by semi-bright coal. The variation range of the maximum reflectance of vitrinite in the No. 4-2 coal seam is between 0.51% and 0.60%, with an average of 0.54%. It belongs to low-rank bituminous coal, and the main types of coal are long-flame coal and non-caking coal. Under the demineralized basis, the content of vitrinite is the highest in the microscopic components of the No. 4-2 coal seam, ranging from 76.2% to 83.4%, with an average of 79.9%. Secondly, the content of exinite is between 1.0% and 21.0%, with an average of 14.0%. The content of inertinite is the lowest, ranging from 1.2% to 18.2%, with an average of 6.1%. (Table 1).

Table 1. Maceral content (on mineral-free basis) and Maximum reflectance of vitrinite of the 4-2 coal seam.

Coal	Maceral content(%, mmf)			Maximum reflectance of vitrinite(%)
	Vitrinite	Liptinite	Inertinite	
4-2	76.2-83.4	1.0-21.0	1.2-18.2	0.51-0.60
	79.9(4)	14.0(4)	6.1(4)	0.54(4)

mmf, on mineral-free basis

3.2 Coal quality

1) Ash yield (Ad).

The raw coal ash yield of the No. 4-2 coal seam in Panji Coal Mine ranges from 7.18% to 28.46%, with an average of 14.13% (Table 2), belonging to extra-low ash - low ash coal. On the plane, the ash content in the study area is generally not high, basically all being extra-low - low ash coal, with only sporadic medium ash coal areas at three boreholes. After flotation, the ash yield significantly decreased to 3.91% - 13.86%, with an average of 8.74%.

2) Volatile Matter (Vdaf).

The raw coal volatile matter yield of the No. 4-2 coal seam in Panji Coal Mine ranges from 43.25% to 54.92%, with an average of 49.47% (Table 2), belonging to high volatile matter coal. After flotation, the volatile matter yield did not change significantly, ranging from 40.09% to 53.85%, with an average of 48.62%.

3) Sulfur Content (St, d).

The total sulfur mass fraction of the raw coal of the No. 4-2 coal seam in Panji Coal Mine ranges from 0.14% to 1.66%, with an average of 0.63% (Table 2), belonging to extra-low - low sulfur coal. On the plane, the 4-2 coal seam is mainly low sulfur coal, with a small range of extra-low sulfur coal and sporadic medium sulfur coal. After flotation, the total sulfur mass fraction is 0.18% - 0.86%, with an average of 0.35%. The analysis of sulfur forms in coal shows that both the raw coal and floated coal of the No. 4-2 coal seam are mainly organic sulfur, followed by sulfide sulfur, and sulfate sulfur is less.

4) Hydrogen to Carbon Ratio (H/C).

The H/C atomic ratio of the raw coal of the No. 4-2 coal seam in Panji Coal Mine ranges from 0.63 to 0.99, with an average of 0.84; the H/C atomic ratio of the floated coal ranges from 0.76 to 1.02, with an average of 0.90, all greater than 0.75 (Table 2).

Table 2. Proximate analysis, H/C, and the contents of harmful elements (S, Cl, F, As) of the 4-2 coal seam.

Coal	A_d/%	V_{daf}/%	$S_{t,d}$%	H/C	Cl/μg/g	F/μg/g	As/μg/g
Raw coal	7.18-28.46 14.13(13)	43.25-54.92 49.47(13)	0.14-1.66 0.63(8)	0.63-0.99 0.84(22)	170-540 330(5)	37-84 57(5)	2-14 5(5)
Float coal	3.91-13.86 8.74(22)	40.09-53.85 48.62(22)	0.18-0.86 0.35(16)	0.76-1.02 0.90(12)	/	/	/

4 Harmful Elements

During the formation process of coal, there will be an enrichment of various trace elements. Among them, some harmful elements will enter into the atmosphere, water, soil and biosphere along with the mining and combustion of coal, causing harm to the environment and human health [9-11]. The harmful elements in coal are important evaluation indicators for the clean utilization of coal and an important part of the research on clean coal geology [12]. Therefore, this study focuses on researching the contents of chlorine, fluorine and arsenic elements in the 4-2 coal seam of the Panji Coal Mine.

4.1 Chlorine (Cl)

The chlorides formed after the high-temperature reaction of chlorine elements in coal will cause severe corrosion to equipment. In addition, the generation of chlorine gas will also cause harm to the surrounding environment and human health. The content of chlorine elements in the raw coal of the 4-2 coal seam in the Panji Coal Mine is between 170 and 540 μg/g, with an average of 330 μg/g (Table 2), and it is mainly extremely low to low chlorine coal as a whole.

4.2 Fluorine (F)

Fluorine element is one of the main harmful elements in coal. Due to its high volatility and high mobility, it is easily released into the atmosphere or water body during the process of coal processing and combustion, thus causing pollution to the surrounding environment and ecosystem. The content of fluorine elements in the raw coal of the 4-2 coal seam in the Panji Coal Mine is 37 to 84 μg/g, with an average of 57 μg/g (Table 2), and it is mainly extremely low to low fluorine coal as a whole.

4.3 Arsenic (As)

During the combustion process of coal, arsenic will be discharged into the atmosphere along with the flue gas, causing great harm to the atmospheric environment and human health. The content of arsenic elements in the raw coal of the 4-2 coal seam in the Panji Coal Mine is 2 to 14 μg/g, with an average of 5 μg/g (Table 2), and it is mainly extremely low to low arsenic coal on the whole.

5 Classification of Coal Cleanliness

The classification of the clean potential of coal stands is one of the essential bases for the classification, quality differentiation, and clean and efficient utilization of coal [12-14]. In line with the evaluation system of the clean utilization potential of coal proposed by Tang et al. (2006) [15], the clean potential of coal in the 4-2 coal seam of the Panji Coal Mine is scrutinized by comprehensively considering factors like ash content, sulfur content, chlorine element, fluorine element, and arsenic element. By comparing the coal quality data of the 4-2 coal seam with the classification scheme of the clean grade, it's concluded that the contents of chlorine element, fluorine element, and arsenic element in the raw coal are relatively low, and thus, it can be categorized as Class I clean coal. The sulfur content is relatively high, corresponding to Class II (relatively clean coal). Meanwhile, the ash content aligns with the classification standard of Class III (less clean coal). Based on the principle of "choosing the lower rather than the higher" in the assessment of the clean potential of coal resources, the clean grade of the raw coal of the 4-2 coal seam is Class III, which falls into the realm of relatively unclean coal (Table 3). After flotation, the ash content is notably reduced and can reach the classification standard of Class II (relatively clean coal), and the sulfur content is also significantly lowered and can meet the classification standard of Class I (clean coal). Hence, the relatively high ash content poses as the most substantial hindrance to the clean utilization of coal in the 4-2 coal seam of the Panji Coal Mine. Due to the lack of data regarding harmful elements after the flotation of the 4-2 coal seam in this study, the classification of the clean grade of the float coal hasn't been explored.

Table 3. Classification of clean level of 4-2 coal seam in Panji Coal Mine.

Coal	A_d %	$S_{t,d}$ %	Cl $\mu g \cdot g^{-1}$	F $\mu g \cdot g^{-1}$	As $\mu g \cdot g^{-1}$	Grade
Classification standard	≤5	≤0.5	≤350	≤100	≤5	I（Clean coal）
	>5~10	>0.5~1	>350~600	>100~150	>5~7	II（relatively clean coal）
	>10~20	>1~1.5	>600~1000	>150~200	>7~10	III（less clean coal）
	>20~40	>1.5~2.5	>1000~1600	>200~300	>10~15	VI（Unclean coal）
Raw coal	14.13	0.63	330	57	5	III（less clean coal）
Float coal	8.74	0.35	/	/	/	/

Note: Raw coal and floating coal data are arithmetic mean values

6 Clean Utilization of Coal

The "Technical Guidelines for Coal Used in Coal Chemical Industry (GB/T 23251-2009)" presents requirements for the optimized configuration and rational planning of coal utilized in the coal chemical industry, and explicitly stipulates that the main types of coking coal that can be employed for coking after washing and selection should not be utilized as coal for coal liquefaction and gasification. This study assessed the clean utilization approaches of the 5th coal seam in Panji Coal Mine in the sequence of coking - liquefaction - gasification. First of all, the main coking coal types after washing and selection (1/3 coking coal, fat coal, coking coal, and lean coal) should be evaluated for coking coal usage. Secondly, the evaluation should be conducted in accordance with the requirements of the evaluation indicators for special coal for liquefaction and gasification.

The 4-2 coal seam of Panji Coal Mine pertains to lignite, long-flame coal and non-caking coal, and is not appropriate for coking coal. In accordance with the evaluation index system of special coal for liquefaction, it is suitable for direct liquefaction coal ((lignite, long-flame coal, non-caking coal, weakly caking coal and gas coal in bituminous coal)). By further comparing the technical requirements for coal quality in the "Technical Conditions for Raw Coal for Direct Liquefaction" GB/T 23810-2009 and the coal quality index system for coal direct liquefaction determined in this study, through the research on the indicators such as volatile matter (V_{daf}), maximum reflectance of vitrinite (Ro, max), hydrogen-carbon atomic ratio (H/C), inertinite content (I, demineralized basis), and ash content (A_d) of the 4-2 coal seam, it was discovered that the volatile matter yield of raw coal of the 4-2 coal seam was within the range of 43.25 - 54.92%, with an average of 49.47%. After flotation, the volatile matter did not undergo a significant change, being within 40.09 - 53.85%, with an average of 48.62%. The volatile matter of both raw coal and float coal was overall greater than 35%; the maximum reflectance of vitrinite was within 0.51 - 0.60%, with an average of 0.54%, which was less than 0.65% overall; the H/C atomic ratio of raw coal was within 0.63 - 0.99, with an average of 0.84; the H/C atomic ratio of float coal was within 0.76 - 1.02, with an average of 0.90, all exceeding 0.75; the inertinite content was within 1.2 - 18.2%, with an average of 6.1%, which was within ≤ 15 vol.%; the ash yield of raw coal was within 7.18 - 28.46%, with an average of 14.13%, which was greater than 12% overall. After flotation, the ash yield decreased conspicuously, being within 3.91 - 13.86%, with an average of 8.74%, which was within 8 - 12% overall.

Based on the aforementioned analysis, the 4-2 coal seam of Panji Coal Mine is not suitable for direct liquefaction coal due to its high ash content. After flotation, the ash content decreased significantly and could be reduced to between 8 - 12%, which could fulfill the classification requirements of direct liquefaction coal and belongs to Grade II direct liquefaction coal (Table 4).

Table 4. Grades of coal used for direct liquefaction in the 4-2 coal seam of Panji Coal Mine.

Coal	V_{daf} %	Ro, max %	H/C	I vol.%	A_d %	Grade
classification standard	>35	<0.65	>0.75	≤15	≤8	I
			0.70~0.75	15.01~45	8~12	II
Raw coal	42.93	0.54	0.84	6.1	14.13	/
Float coal	41.66	0.54	0.90	6.1	8.74	II

Note: Raw coal and floating coal data are arithmetic mean values

7 Conclusions

(1) The 4-2 coal seam of Panji Coal Mine has relatively low contents of chlorine, fluorine and arsenic elements, and relatively high contents of ash and sulfur. The high ash

content is the main obstacle to the clean utilization of coal in Panji Coal Mine. According to the evaluation system of coal clean utilization potential, a preliminary evaluation of the cleanliness grade of the coal seam is carried out. The cleanliness grade of raw coal in the 4-2 coal seam is Grade III, which belongs to relatively unclean coal.

(2) The coal types of the 4-2 coal seam in Panji Coal Mine are mainly lignite, long-flame coal and non-caking coal. The content of inertinite group is relatively low. On the whole, it has the characteristics of extremely low - low ash content, high volatile matter and high hydrogen to carbon atomic ratio. The float coal meets the evaluation index for direct coal liquefaction and is suitable as Grade II direct coal liquefaction coal.

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