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INVESTIGATION OF SHIVEE-OVOO COAL AND IT'S PYROLYSIS PRODUCTS

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The characterization of the initial of Shivee-Ovoo coal of Mongolia, it's hard and liquid pyrolysis products was performed. Shivee-Ovoo coal is oxidized brown coal of lignite type with B2 mark. The yields of obtained hard, liquid and gas products of pyrolysis at different heating temperatures was determined. The porosity of raw coal, char of pyrolyzed coal and activated carbon of pyrolyzed char was determined by SEM analysis. The pyrolysis products of coal was investigated by IR-spectroscopy and GC/MS chromatography.
Keywords: coal, pyrolysis, activated carbon, spectroscopy, chromatography, porosity, pyrolysis products

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The Shivee-Ovoo brown coal deposit is one of the largest in the «Nyalga-Choir» coal basin in the central economic region of Mongolia. Estimated coal resources is 2,7 billion tones [1, 2]. The Shivee-Ovoo coal deposit has been worked as a open-cast mine since 1990 and is used in thermal power stations in Ulaanbaatar city. The Shivee-Ovoo coal deposit is located in the territory of the village «Dalanjargalan» of the East-Gobi province 300 km southeast of Ulaanbaatar [2].

Results of our previous investigation on gasification of Shivee-Ovoo coal have shown that it is a reactive fuel under conditions that produce combustible gases, because of its high content of volatile matters — 42,57% [3]. Also the Shivee-Ovoo coal has been non-isothermally pyrolysed in a thermogravimetric analyser and in a fixed bed gasification reactor to determine the influence of heating temperature and heating rate on the thermal degradation of the coal sample [4].

Experimental

The analytical coal samples of Shivee-Ovoo deposit were prepared for analysis according to ASTM D 2797. The main technical characteristics such as proximate and ultimate analysiswere performed according to Mongolian National Standards MNS 656–79 (moisture content), MNS 652–79 (ash yield), MNS 654–79 (volatile matter yield), MNS 669–87 (gross calorific value) and MNS 895–79 (sulphur content).

For the determination of mineral content in Shivee-Ovoo coal have been obtained completely burned ashes of coals during slowly and continuously burning in furnace at 200–850°C. The content of mineral elements in coal samples and their oxides have been determined by using of X-ray fluorescence spectrometry.

The small-scale pyrolysis experiments of coal samples were performed in a laboratory quarts retort (tube) which could contain air dried and powdered to a particle size < 0,2 mm 1 g of coal sample. The retort was placed in a horizontal electric tube furnace with a maximum heating temperature of 950°C. A chrome-alumel thermocouple was immersed in the tube furnace to measure the actual heating temperature. The pyrolysis experiments have been carried out at different heating temperatures 200–700°C with constant heating rate 20°C/min. First of all the quarts retort with coal sample was heated for example to 600°C with heating rate 20°C/min. and kept at 600°C for 80 min. The retort was connected with a thermostable glass tube heated also in a tube furnace at 80°C for collecting of tars and this tube is also connected with a air-cooled glass vessel for collecting of pyrolysis water. The glass vessel for pyrolysis water is also connected with a thin glass tube for non-condensable gases. The yields of pyrolysis products including solid residue (coal char), tar (condensed liquid product) and pyrolysis water determined by weighing, and the yield of gases by differences.

The preparative-scale pyrolysis experiments of coal sample was performed in a laboratory vertical cylindrical retort made by stainless steel which could contain 1000 g of sample. The retort was placed in an electric furnace (SNOL) with a maximum temperature of 950°C. A chrome-alumel thermocouple was immersed in the coal bed to measure the actual heating temperature and an equipment for temperature control (potentiometer). The retort was connected with a air-cooled iron tube and water-cooled laboratory glass condenser and a collection vessel for the condensed of liquid product (tar and pyrolysis water). The non-condensable gases after water-cooled condenser were left the system through a thin glass tube. The yields of products including hard residue (char), tar and pyrolysis water determined by weighing in %, and the yield of gases by difference.

The liquid condensed by product of coal pyrolysis consists from tar and pyrolysis water. They form an unmixed two layers and can be separated easily by separating glass funnel. The upper layer is tar (viscous liquid) with black-brown color and unpleasant smell. The bottom layer is pyrolysis water (no viscous liquid) with bad smell and brown color. The final cleaning of tar from the pyrolysis water usually use thermally treated $CaCl_2$ by mixing and separating (filtering or centrifuging).

The Fourier transform infrared spectroscopy (FTIR) spectra of the samples were obtained on a Interspec 200-X series of FTIR spectrometers with PIKE Diffusion IR accessories using a KBr disc containing 1 % finely ground samples. All the spectra were measured in the frequency range of 4000 to 400 cm^{-1}, and 32 scans were taken per sample.

First of all organic bases and organic acids were removed from the pyrolysis tar of Shivee-Ovoo coal and so purified tar is called as a «neutraloil».

The fractions were used for GC/MS analysis (Agilent 7890A Agilent 5975C GCMS).

Results and discussion

The results of proximate and ultimate analysis of coal samples from Shivee-Ovoo deposit are shown in Table 1.

Table 1

Proximate and ultimate analyses of Shivee-Ovoo coal

Sample	Proximateanalysis, %				Ultimate analysis, %			
	Moisture, W^a	Ash, A^d	Volatile matter, V^{daf}	Caloric value, Q^{daf}, kcal/kg	Carbon, C^{daf}	Hydrogen, H^{daf}	Sulfure total, St	Oxygen and others, $(N+O)^{daf}$
Shivee-Ovoo coal	13,41	21,17	42,57	6501,2	71,36	4,99	1,06	22,59

The results of proximate and ultimate analysis in Table 1 for example the content of volatile matter, the ratio of H/C=0.84, carbon and oxygen content indicate that coal from Shivee-Ovoo deposit is a low rank B2 (ISO 11760) brown coal. The content of total sulfure is not high and not so dangerous for the environment.

To characterize the organic matter of the Shivee-Ovoo coal has been analyzed by IR analysis (Fig. 1).

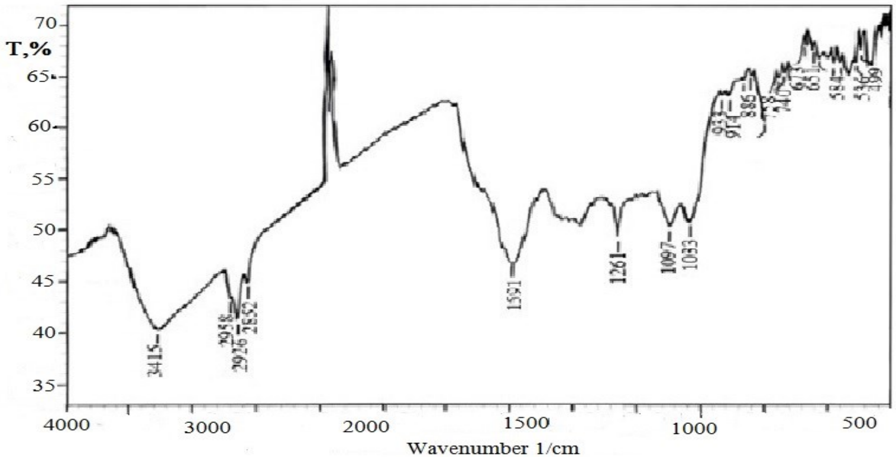


Fig. 1. The IR spectra of coal from Shivee-Ovoo deposit

On the IR spectra of Shivee-Ovoo coal there are several week absorption bands for -CH aromatic group at 698, 752, 800 cm^{-1} and for aliphatic -CH; -CH_2 and –CH_3 groups with middle intensity at 1249 cm^{-1} and a sharp bands with higher intensity at 2854-2923 cm^{-1}. And and also a strong absorption bands for > C=O groups at 1600 cm^{-1}, week bands for -O- groups at 1400 cm^{-1} and for C-O- groups at 1000, 1050 cm^{-1}. A unsharp and strong band for -OH and -NH groups at 3400 cm^{-1}. Therefore the coal organic mass of Shivee-Ovoo coal consist mainly aliphatic, aromatic and aromatic-aliphatic structures with above mentioned groups inside.

The coal sample was burned completely and the ash was analyzed by rentgenfluorecence analysis. the chemical composition for the characterization of inorganic matter of the coal from Shivee-Ovoo deposit was determined (Table 2).

Table 2

Chemical composition of coal ash from the Shivee-Ovoo deposit (wt %)

Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	Mn_2O_3	Fe_2O_3	TiO_2	SrO	Cu	Zn
1.33	5.21	10.53	27.72	0.57	18.21	1.4	28.87	0.62	5.72	0.81	0.19	0.01	0.04

As seen in the Table 2, there are oxides of CaO and SiO_2 have highest concentrations, oxides of Al_2O_3, MgO, SO_3 and Fe_2O_3 have medium concentrations and other oxides have low concentrations.To determine the character (acidic or basic) of of the coal was calculated the ratio between following sum oxides: Fe_2O_3 + CaO + MgO

+ Na_2O + K_2O/SiO_2 + Al_2O_3 + Ti_2O > 1. The ration is less than 1 and it means the coal ash of Shivee-Ovoo deposit has a basic character.

The thermogravimetric analysis is a most useful method for the investigation on thermal decomposition (in argon atmosphere Hitachi, TG/DTA7300) and thermal stability of natural organic resources including coals.

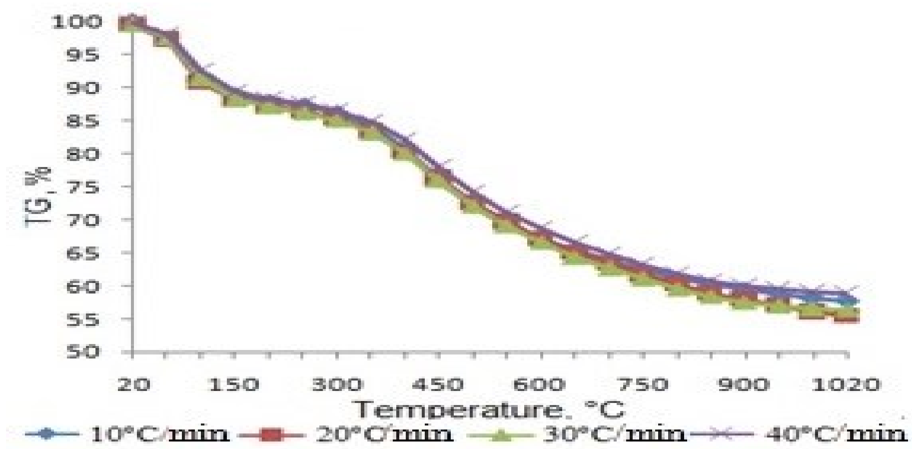


Fig. 2. TG curves of the Shivee-Ovoo coal at different heating rates

The thermal decomposition of Shivee-Ovoo coal in argon gas was investigated by thermogravimetric analyzer in 20–1100°C heating temperatures at different heating rates of 10, 20, 30, 40°C/min. and the TG, DTA and DTG curves are shown in Fig. 2, 3 and 4.

The thermal decomposition of Shivee-Ovoo coal in argon gas was investigated by thermogravimetric analyzer in 20–1100°C heating temperatures at different heating rates of 10, 20, 30, 40°C/min. and the TG, DTA and DTG curves are shown in Fig. 2, 3 and 4.

The TG curves (Fig. 2) of the Shivee-Ovoo coal at different heating rates show that all curves are similarly.

The heating of the Shivee-Ovoo coal sample at temperatures range 25–1000°C and different heating rates in nitrogen atmosphere show that the thermal decomposition of coal ended with a 55–60% weight loss and 40–45% hard residue 1000°C (Fig. 2). The TG curve in Fig. 3 consists of different temperature intervals (steps) such as 25–250; 250–550; 550–850; 850–1000°C. In the first step (25–250°C) the weight loss is due to the release of some absorbed gas and moisture from the coal sample. In the second step (250–550°C) intensive thermal decomposition of the organic matter of the coal samples start forming liquid (tar and pyrolysis water) and gas products. In the third step (550–850°C) the weight loss strongly decreases, which is an indication for ending the thermal decomposition and starting carbonization of the coal sample. In the fourth step (850–1000°C) the weight loss slowly increases, which is related with the release of gas, e.g. CO_2, H_2, CO from the mineral matter of coal sample.

From the TG curve in Fig. 2 have been determined the thermal stability indices ($T_{5\%}$, $T_{15\%}$, $T_{25\%}$) of each heating rate of the Shivee-Ovoo coal and the results are given in Table 3.

Table 3

The thermal stability indices of the Shivee-Ovoo coal

No	Heating rates, ^{0}C/min.	Thermal stability indices, °C		
		$T_{5\%}$	$T_{15\%}$	$T_{25\%}$
1.	10°C/min.	68.43	330.89	330.89
2.	20°C/min.	67.46	308.81	465.18
3.	30°C/min.	71.75	300.97	461.55
4.	40°C/min.	79.76	344.06	490.64
	Averaged 25°C/min.	71.85	321.18	437.07

On the basis of the determined thermal indices in Table 3 have been calculated an averaged heating rate — 25°C/min. and related averaged thermal stability indices as $T_{5\%}$ =71,85°C; $T_{15\%}$ = 321,18°C; $T_{25\%}$ = 437.07°C for Shivee-Ovoo coal. These indices indicate that the organic mass of Shivee-Ovoo coal has a lower thermal stability or easy decomposes under heating.

First minimum peak of DTA at 160°C shows a endothermic reaction process related with releasing adsorbed gas and moisture from the coal organic mass of the sample and a bid exothermic reaction peak at 400°C related with intensive thermal destruction of the organic mass of the coal sample. The DTG curves in Fig. 3 consist of 2 zones and indicate clearly increasing the decomposition rate of coal organic mass vs increasing of heating rate. DTG curves are schown releasing of moisture and adsorbed gas at about 100°C a and also thermal destruction reactions of coal organic mass at about 450^{o}C are with maximum rate.

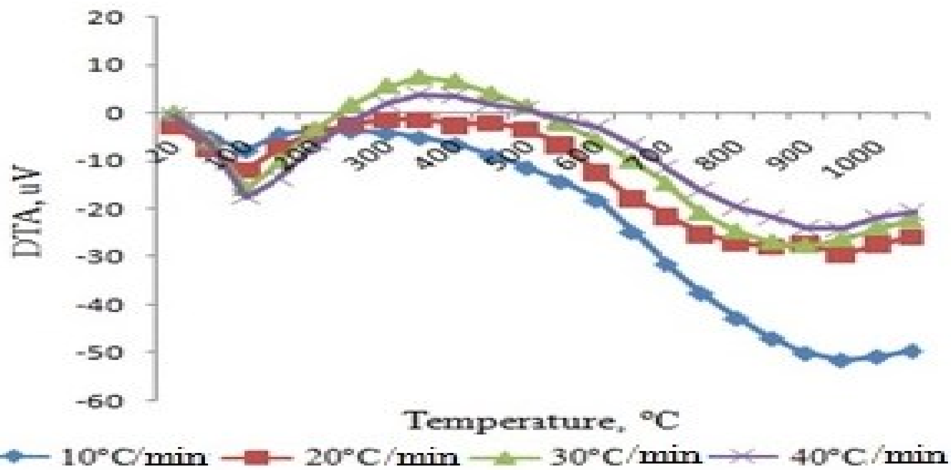


Fig. 3. DTA curves of the Shivee-Ovoo coal at different heating rates

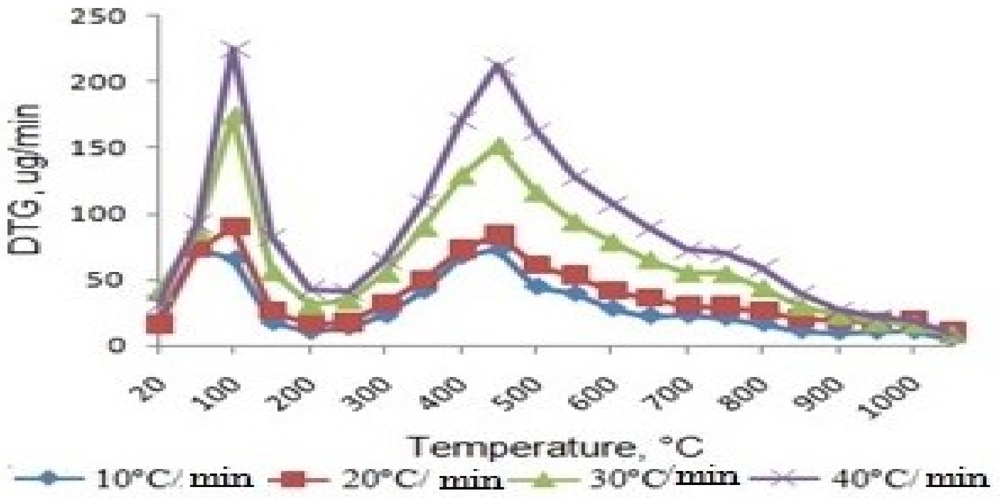


Fig. 4. DTG curves of the Shivee-Ovoo coal at different heating rates

The pyrolysis is a one of the often used thermal processing of brown coals to produce a solid (hard residue or char or semicoke), condensed liquid (tar) and uncondensed gas product. Shivee-Ovoo coal was pyrolized in a standard quartz retort at different heating temperatures (200–700°C) for 80 min and the yields of char, tar, pyrolysis water and gas was determined (Fig. 5).

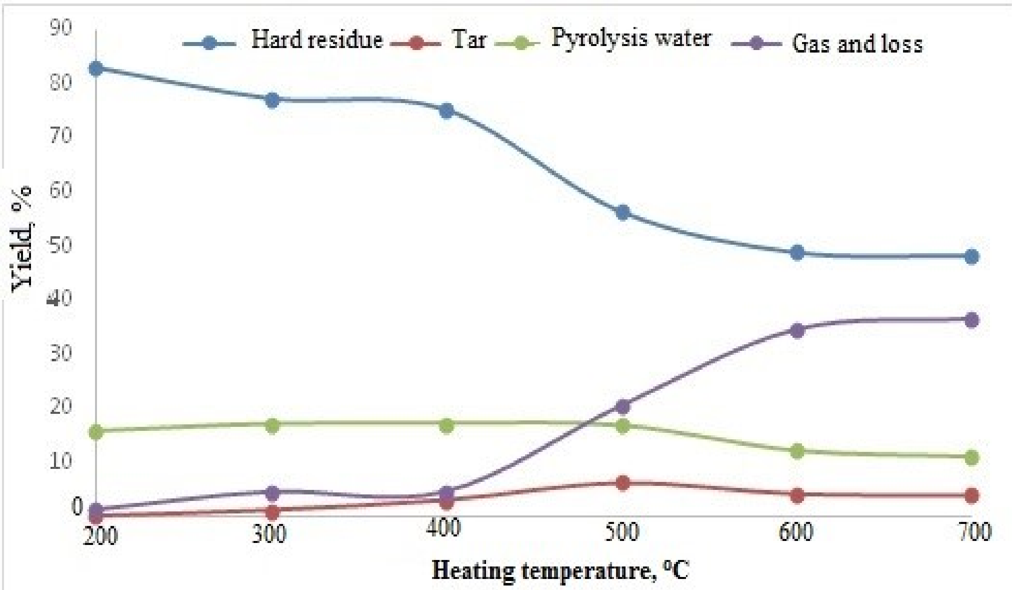


Fig. 5. The yields of pyrolysis products vs different heating temperatures

The results of the pyrolysis of Shivee-Ovoo coal in Fig. 5 show that the optimal heating temperature is 500°C, in which the yield of tar is higher. The yield of all thermal decomposition products such as liquid and gas products (44%) shows that there is an intensive thermal decomposition of the coal organic mass with higher degree of conversion. As it is known that the organic mass of low rank brown coal (lignite) characterizs with lower thermal stability than high rank (bituminous) coal and therefore brown coals are more suitable for gasification and liquefaction.

Table 4

Main technical characteristics of the pyrolysis hard residue and initial coal of Shivee-Ovoo deposit

№	Shivee-Ovoo coal	Main technical characteristics,%			
		Moisture,W^a	Ash, A^d	Volatile matters, V^{daf}	Caloric value, Q^{daf}, ккal/кg
1.	Initial coal	13,41	21,17	42,57	6501.20
2.	Pyrolysis hard residue	0,10	27,42	16,20	7337.96

The solid product (hard residue or semi coke) after the pyrolysis Shivee-Ovoo coal is one of the main product and can be used as smokeless fuel and activated carbon after briquetting and activation. For this reason have determined the main technical characteristics of the hard residue and compared with the same characteristics of the initial coal (Table 4).

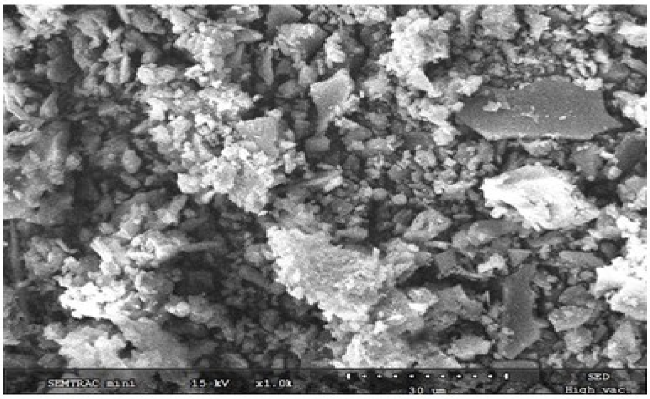
The proximate analysis results of hard residue after pyrolysis of Shivee-Ovoo coal (Table 3) show that the volatile matter content decreased 3 times and increased caloric value in comparison with the initial coal characteristics, indicating that it can be used as smokeless fuel [8].

One of the most important applications of the hard residue after thermal processing is to produce activated carbon. For this reason the hard residue produced after pyrolysis was activated by preheated water steam at 800°C for 120 min.

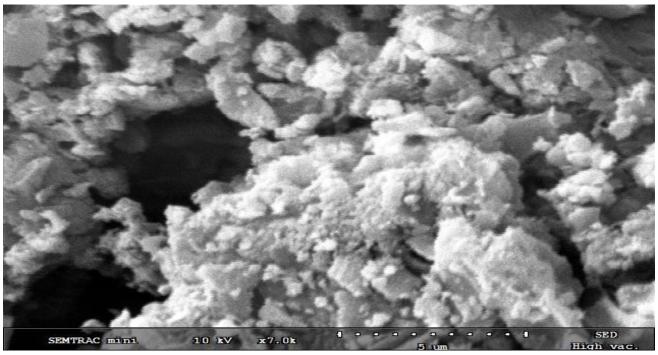
The images of scanning electron microscopes (SEM) of prepared activated carbon from pyrolyzed hard residue (Fig. 6b) in comparison with initial coal sample (Fig. 6a) are different as presented in Fig. 6.

The SEM image of initial coal sample (Fig. 6a) has compact solid pieces. The SEM images of carbonized and activated coal sample (Fig. 6b) show porosity structure with meso and macro pores in comparison with that of initial coal sample.

The pyrolysis tar is most important product with unknown properties and composition. Therefore we focused on more detailed investigation of this tar.



a



b

Fig. 6. The SEM photograph of initial coal sample of Shivee-Ovoo (a) and it's activated carbon sample (b).

First of all the tar was completely removed from the pyrolysis water by, centrifuging and drying with thermally treated calcium chloride and filtering. So purified tar tested by IR analysis and the FT IR spectra is shown in Fig. 7.

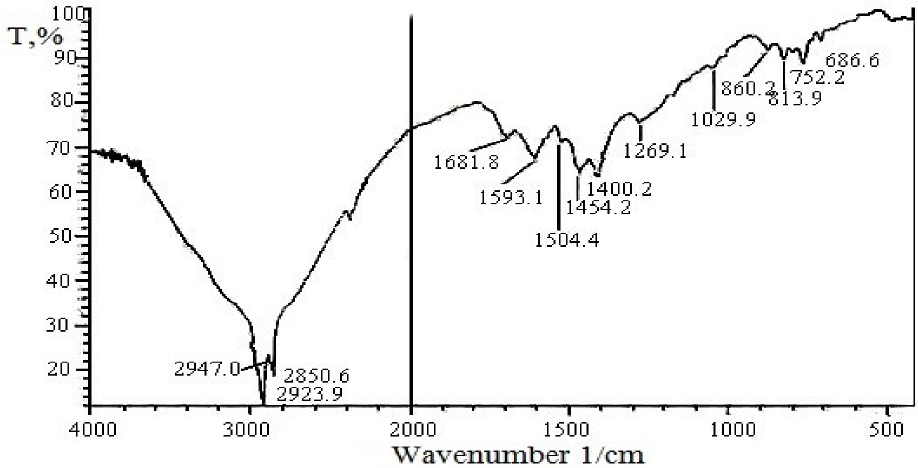


Fig. 7. The FTIR spectra of liquid tar product after pyrolysis

In the FTIR spectra of tar product after pyrolysis, low intensity absorption bands were observed for H of aromatic -CH group at 686, 752, 813 cm^{-1} and for H of aliphatic -CH; $-CH_2$ and $-CH_3$ groups at 1269 cm^{-1} and their sharp bands with highest intensity at 2850-2947 cm^{-1}. Absorption bands with middle intensity for O containing groups such as for >C=O groups at 1593 cm^{-1}, for -O- groups at 1454 cm^{-1}. Therefore the tar product of Shivee-Ovoo coal after pyrolysis consists of mainly aliphatic, aromatic and aromatic-aliphatic compounds with above mentioned functional groups in their molecules.

The chemical composition of the tar determined by chemical analysis in group organic compounds and the results are given in Table 5.

Table 5

The chemical composition of the tar in group organic compounds

Sample	The chemical composition of the tar, мас. %					
	free carbons	organic bases	organic acids	phenols	asphalteins	neutral oils
Pyrolysis tar	3.93	0.25	0.06	0.8	13.06	81.9

The date in Table 5 show that the neutral oils are the main component with highest and asphalteins, free carbons are with middle content. The contents of organic bases, organic acids and phenols are lowest.

Also the pyrolysis tar of Shivee-Ovoo coal was tested by an air distillation and obtained several fractions with different boiling temperature ranges and the yield and some other determined properties are given in Table 6.

Table 6

The yields of pyrolysis tar of Shivee-Ovoo coal

Boiling temperature range, °C	Yield fraction, %	Refractive index	Color	Description
Startin loiling -180°C	15,93	1,342	yellow	light fractions
180-330°C	15,44	1,529	brown	middle fractions
More than 330°C	44,53	-	Black-brown	heavy fractions
loss	24,10	-	-	-

The date in Table 6 show that the main product of distillation of the pyrolysis tar of Shivee-Ovoo coal is the heavy fractions, followed light and middle fractions with same yields. After removing of the toxic organic compounds such as organic bases, organic acids and phenols these fractions can be used as gasoline (light fractions), diesel (middle fractions) and oil products (heavy fractions).

As mentioned above organic bases and organic acids were removed from the pyrolysis tar of Shivee-Ovoo coal and so purified tar is called as a «neutraloil».

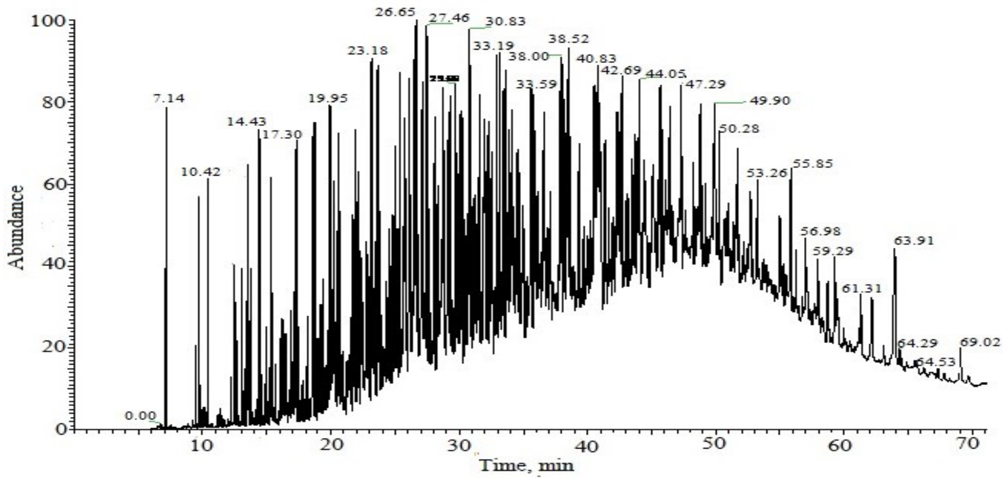


Fig. 8. GC/MS chromatogram of soluble in hexane fraction of the neutral oil from the pyrolysis tar of Shivee Ovoo coal

The solubility in hexane, toluene and methylenchloride-methanol and chemical composition of the neutral oil investigated by silica gel chromatography and GC/MS analysis and the results of GC/MS chromatograms are presented in Fig. 8, 9 and 10.

On the bases of Fig. 8 summarized all aliphatic compounds and the results are given in Table 7.

Table 7

The identified aliphatic compounds of soluble in hexane fraction of the neutral oil from the pyrolysis tar of theShivee Ovoo coal

Identified aliphatic compounds	content, %
Alkanes C_6-C_{35}	13.92
Cycloalkaнes C_7-C_{35}	10.59
Alkenes C_7-C_{35}	18.28
Total	**42.79**

The date in Table 7 show that the most identified aliphatic compounds are C_6–C_{35} paraffin's, C_7-C_{35} alkenes, and C_7-C_{35} cycloalkenes. All 22 compounds identified from all registered 68 peaks in the GC/MS chromatogram of soluble in hexane fraction of the neutral oil from the pyrolysis tar of Shivee Ovoo coal.

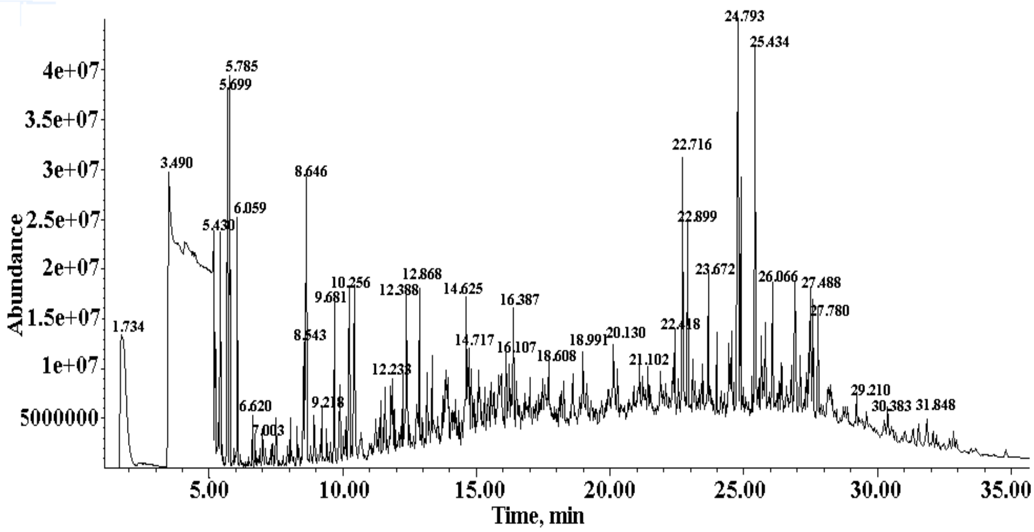


Fig. 9. GC/MS chromatogram of soluble in toluene fraction of the neutral oil from the pyrolysis tar of Shivee Ovoo coal

On the bases of Fig. 9 summarized all aromatic compounds and the results are given in Table 8.

The date in Table 8 show that the most identified aromatic compounds are monocyclic and polycyclic aromatic compounds such as C_7-C_{10} derivatives of benzene, 2 cycloaromatics such as derivatives of naphthalene, 3 cycloaromatics such as derivatives of anthracene and phenanthrene, 4 cycloaromatics such as derivatives of pyrene and some heteroatomic aromatic compounds in the soluble in toluene fraction of the neutral oil from the pyrolysis tar of Shivee Ovoo coal.

Table 8

The identified aromatic compounds of soluble in toluene fraction of the neutral oil from the pyrolysis tar of Shivee Ovoo coal

Identified aromatic compounds		content, %
1 cycloaromatics	C_7	3.26
	C_8	8.88
	C_9	14.55
	C_{10}	4.19
2 cycloaromatics	Naphthalene, their derivatives	8.02
3 cycloaromatics	Anthracene and phenanthrene, their derivatives	8.87
4 cycloaromatics	Pyrene, their derivatives	3.75
heteroatom aromatic compounds		28.21
Total		79.73

All 45 compounds identified from all registered 100 peaks in the GC/MS chromatogram of soluble in toluene fraction of the neutral oil from the pyrolysis tar of Shivee Ovoo coal.

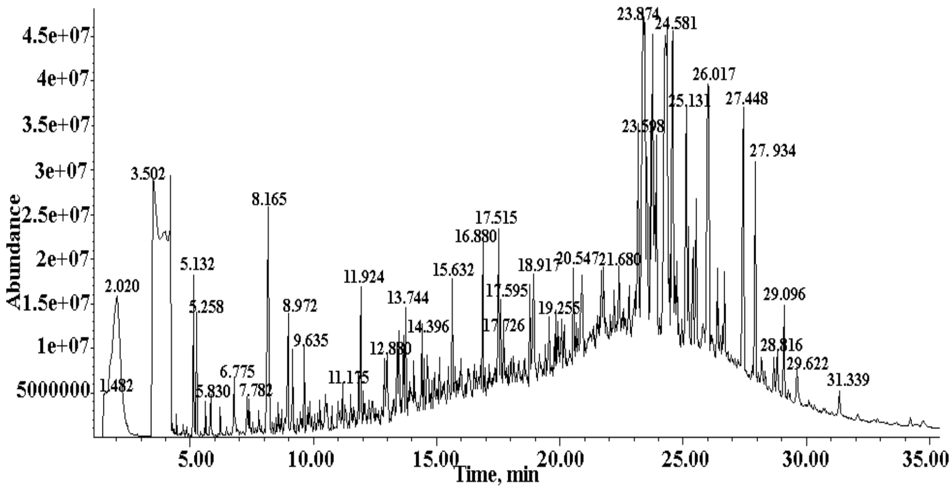


Fig. 10. GC/MS chromatogram of soluble in methylenchloride-methanol fraction of the neutral oil from the pyrolysis tar of Shivee Ovoo coal

On the base of Fig. 10 summarized all oxygen containing organic compounds and the results are given in Table 9.

Table 9

The oxygen containing organic compounds of soluble in methylenchloride-methanol fraction of the neutral oil from the pyrolysis tar of the Shivee Ovoo coal

Identified compounds	Content, %
Alcohols	22.59
Phenols	7.94
Esters	1.59
heteroatom compounds (nitrile)	2.44
Total	**34.56**

The date in Table 9 show that the most identified oxygen containing organic compounds are aliphatic alcohols, phenols, esters and heteroatoms compounds such as nitriles in the soluble in methylenchloride-methanol fraction of the neutral oil from the pyrolysis tar of Shivee Ovoo coal.

All 21 compounds identified from all registered 100 peaks in the GC/MS chromatogram of soluble in methylenchloride-methanol fraction of the neutral oil from the pyrolysis tar of Shivee Ovoo coal.

Conclusion

1. On the base of proximate and ultimate analysis have been confirmed that the Shivee-Ovoo coal is a low-rank lignite coal of B2 mark and it is suitable for thermal processing including pyrolysis.
2. The thermal degradation process of Shivee-Ovoo coal was investigated by thermogravimetric analyzer and first time the thermal stability of the coal sample by determination of thermal indices was determined.
3. The results of pyrolysis experiment of Shivee-Ovoo coal show that 56,00% of coal organic mass remained as a hard residue after pyrolysis. The yield of all liquid and gas products is 44,00% at the optimal heating temperature 500°C, which is showing that there was an intensive thermal decomposition of the coal organic mass with higher degree of conversion.
4. The chemical composition of pyrolysis tar of Shivee-Ovoo coal in group organic compounds show that the tar consists mostly neutral oils with highest content - 81,9%, asphalteines — 13,6%, free carbons — 3,93% and organic bases, organic acids, phenolic compounds are less than 1,0%.
5. Several fractions of pyrolysis tar of Shivee-Ovoo coal was obtained with different boiling temperature ranges.
6. The proximate analysis results of hard residue after pyrolysis show that the volatile matter content decreased 3 times and increased caloric value in comparison with the initial coal characteristics, indicating that there was an intensive thermal decomposition of the coal organic mass and it can be used as smokeless fuel.
7. The SEM image of carbonized and activated coal sample shows a porosity structure with meso- and macro -pores in comparison with that of initial coal sample.
8. The solubility and chemical composition of neutral oil isolated from the pyrolysis tar of Shivee-Ovoo coal are investigated by GC/MS analysis.

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ИССЛЕДОВАНИЕ УГЛЯ ШИВЭЭ-ОВОО И ПРОДУКТОВ ЕГО ПИРОЛИЗА

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Проведена характеристика исходного угля Шивээ-Овоо Монголии, его твердых и жидких продуктов пиролиза. Уголь Шивээ-Овоо представляет собой окисленный бурый уголь лигнитного типа марки В2. Определены выходы полученных твердых, жидких и газообразных продуктов пиролиза при различных температурах нагрева. Пористость необработанного угля, полукокса пиролизованного угля и активированного угля пиролизованного полукокса была определена с помощью SEM-анализа. Продукты пиролиза угля исследованы методами ИК-спектроскопии и ГХ/МС хроматографии.

Ключевые слова: уголь, пиролиз, активированный уголь, спектроскопия, хроматография, пористость, продукты пиролиза.