Effect of N₂ and CO₂ on shale oil from pyrolysis of Estonian oil shale

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Abstract

A kukersite oil shale sample from Estonia was pyrolyzed using a Fischer assay method under N₂, N₂/steam, CO₂ and CO₂/steam environments. The thermal behavior of the oil shale sample was also studied using TGA and DSC with similar conditions. Also, several properties of produced oils were measured and FTIR analysis was carried out to compare the molecular structure of the derived oils. The presence of steam increased the liquid and gaseous yields, and also caused a greater weight loss in the oil shale. The pyrolysis tests in both the CO₂ and N₂ atmospheres produced oils with relatively similar properties however, the molecular structure was different.

KEYWORDS: *oil shale, fischer assay, pyrolysis, steam, CO₂, N₂*

Novelty statement

Pyrolysis of oil shale under nitrogen and/or steam in different process conditions has been widely studied by many researchers. However, the number of studies on CO₂ pyrolysis of oil shale seems to be rare. Therefore, a kukersite oil shale sample from Estonia was pyrolyzed and its thermal behavior under N₂, N₂/steam, CO₂ and CO₂/steam environments were studied. This article provides useful information about the oil shale decomposition process as well as the properties of oil derived under a CO₂ atmosphere.

Introduction

Fossil fuels, such as crude oil, natural gas and coal, provide most of the energy in the world [1]. Oil shale is another widely available fossil fuel, although less used. It is a sedimentary rock that contains significant amount of organic matter called kerogen [2]. Oil shale has attracted lots of interest due to the large amount of available oil shale deposits [3] as well as the possibility of utilizing them as a source of energy and chemicals [4]. The processing of oil shale to produce shale oil is often considered to be costly with a large environmental impact. For this reason, oil shale has not been widely utilized. However, some countries such as Estonia use oil shale extensively to supply their domestic energy [5]–[7].

The chemical composition and physical properties of kerogen vary widely depending on the geographical locations, deposit conditions and oil shale formation conditions. Understanding the characteristics of the oil shale kerogen is essential for its beneficial utilization [8]. The organic matter in the oil shale is classified into two groups: soluble bitumen and insoluble kerogen [9], of which about two thirds can be turned into oil by means of pyrolysis [10].

The production of shale oil via pyrolysis has been one of the main methods of oil shale valorization. Pyrolysis takes place in the absence of oxygen at around 500°C, causing oil shale kerogen to decompose into oil vapor compounds, hydrocarbon and non-hydrocarbon gases, pyrogenic water and semi coke [11]. Among the technologies used, this low temperature pyrolysis has been of more interest for oil shales with a high oil yield [12]. The Fischer assay is a standard lab method used to estimate the oil yield by applying a slow heating rate. Utilizing such pyrolysis methods can be a beneficial way to analyze and associate the produced oil, gas and solid residue compositions with their corresponding test conditions, which results in improving the quality and quantity of the shale oil [13].

Pyrolysis of oil shale under nitrogen and/or steam in different process conditions has been widely studied by many researchers. However, using CO₂ as the purge gas has relatively recently attracted attention, and therefore, the number of studies on CO₂ pyrolysis of oil shale seems to be small [14]–[19]. Tang et al. [14] studied the activation energy of several oil shales and found that a CO₂ atmosphere decreased the activation energy due to higher reactivity of long-chain organics under CO₂ in which lighter hydrocarbons were produced. They then concluded that using CO₂ could enhance the decomposition of oil shale. Consequently, Lee and Joshi [20] reported that exploiting CO₂ as the carrier gas can enhance the oil production by 7-25%, compared to N₂ under similar test conditions. However, Fang-Fang et al. [16] studied oil shale pyrolysis under N₂ and CO₂ and found that at lower temperatures (up to 500°C), both sweep gases showed almost identical behavior. Furthermore, they reported that the activation energy under CO₂ is almost the same as that of in N₂ at this temperature range; however, at higher temperatures of 600-1000°C, CO₂ increased the activation energy. In addition, they showed that CO₂ pyrolysis produced shale oil containing longer chain hydrocarbons than the oil produced under N₂. Also, in another study, Zhao et al. found that the activation energy of oil shale pyrolysis in N₂ atmosphere is higher. They explained that since the heat capacity of N₂ is higher than CO₂ therefore, the heat transfer resistance is larger as well, leading in greater dispersion of oil shale pyrolysis. [21]. These results show that different oil shales - due to their complex structures and different properties - show different behaviors and therefore, predicting them may not lead into the most correct conclusion. Tucker et al. [17] compared the oil yields when retorting under CO₂ and N₂ and reported that oils produced from them are quite similar. They also found that the most substantial difference is that the yield under CO₂ contains more mid-distillate fractions and also has a narrower molecular-weight distribution, and thus is a higher quality oil. The latter result was similar to what Polasy and Lee [19] obtained in their study on initial and final boiling points as well as the boiling range distribution of various shale oils under CO₂ and N₂ retorting and suggested that using CO₂ as a sweep gas increased the quality and quantity of the shale oil. Furthermore, other researchers [18] investigated oil shale retorting under CO₂ and N₂ and found that the chemical compositions of the derived shale oils were different. They also concluded that retorting in CO₂ resulted in production of oils with shorter aliphatic chains compared with N₂, and reduced the abundance of n-alkanes and n-alkenes and suggested that CO₂ tends to preserve the aromatic structure of kerogen, whereas N₂ retorting tends to promote the formation of aliphatic compounds. Therefore, CO₂ appears to play an important role on final products when utilized in the pyrolysis process. The aim of the present research is to study the thermal behavior of kukersite oil shale under a CO₂ atmosphere and compare the yields and properties with those from retorting in N₂ to acquire a deeper understanding of the decomposition process and its impact on liquid products. The evolution and analysis of gaseous products were presented in the second part of this study.[22]

Experimental section

Fischer assay

The Fischer assay is a standard laboratory method used to estimate the oil yield of an oil shale. 50 g of kukersite oil shale with a particle size of 500-710 µm was placed in a Fischer Assay retort. The Fischer assay retort was subjected to four different gaseous environments; CO₂, CO₂/steam, N₂ and N₂/steam. These gases were injected into the reactor using a tube which was placed through the retort lid. The flowrate used for tests without steam was 21 ml/min and for the runs with water vapor, water was injected at 0.1 ml/min and the flowrates of CO₂ and N₂ were set at 10 ml/min. In order ensure that the system was fully purged, the sweep gases were fed through the retort for one hour before beginning the experiment. Also, for the tests in the presence of water vapor, the water was first preheated to 150°C before entering into the retort. The retort was then heated up to 500°C at 10°C /min, from 500°C to 520°C for 20 minutes and held at 520°C for another 20 minutes. To take the possible loss of water into account, three blank runs were made with water injection only. The Fischer Assay enables us to calculate the amount of oil and water, gas, and solid residue produced. The weight of gas produced was computed by difference based on the material balance.

Other analytical methods

Thermal analysis

Thermogravimetric analysis (TGA) of the oil shale samples was conducted using a Netzsch STA 449 F3 Jupiter and differential scanning calorimetry (DSC) analysis was performed using a NETZSCH 204HP Phoenix DSC. The tests were performed under the same conditions as the Fischer Assay in both N₂ and CO₂ environments. The crucibles were filled with about 10 mg of the shale sample. In TGA Pt/Rh alloy crucibles with removable thin-walled Al₂O₃ liners were used, while in DSC open Al-crucibles were used. To ensure reproducibility, the tests for each atmosphere were conducted at least three times.

FTIR

An Interspec 301-X spectrometer fitted with an ATR accessory were used to measure the IR spectra for the oil samples. The sample spectra were analyzed in the wavenumber range of 600-4000 cm⁻¹ at a resolution of 1 cm⁻¹. For each sample, the average of ten scans was used to ensure the repeatability of the spectra and also to reduce the effect of noise. The estimated standard uncertainty and estimated expanded uncertainty (95% level) are 0.00053 and 0.0012 absorbance units (on average), respectively.

Elemental Analysis

Elemental analysis was performed using a Vario MACRO CHNS Cube system. The estimate of expanded relative uncertainty for each element would be as follows: carbon (1.11%), nitrogen (16.56%), hydrogen (2.56%) and sulfur (5.7%). Note that these are relative uncertainties. The relative uncertainty of the nitrogen content seems high simply because the nitrogen content in the samples is low.

MW, RI and density

Other oil properties such as the density, molecular weight and refractive index were also measured. The densities of the oil samples were measured at 15°C and 20°C using a DMA 5000M (Anton Paar GmbH, Austria). In order to check the performance of the device, before and after each experiment the density of air and water were measured. The estimated standard uncertainty and expanded uncertainty (95% level) of the measurements for oil samples is 0.00015 g/cm³ and 0.0003 g/cm³, respectively. The refractive index of the samples was measured using an Abbemat HT refractometer (Anton Paar GmbH) at 20°C and 589.592 nm. Also, water was used before and after each sample to check the performance of the device. The standard uncertainty and expanded uncertainty (95% level) for the device are estimated to be 0.0011 and 0.0021. Molecular weight was measured using a Knauer K-7000 vapor pressure osmometer (Wissenschaftliche Gerätebau Dr Ing Herbert KNAUER GmbH, Germany). Also, it should be noted that estimated standard uncertainty and the expanded uncertainty (95% level) are 7 g/mol and 14 g/mol.

Results and discussion

Oil Shale analysis

Kukersite oil shale from the Ojamaa mine was used throughout the study. The characteristics of kukersite oil shale used in this work are given in Table 1. More detailed analysis of the oil shale can be found in the literature. [23] The elemental analysis of the shale sample indicated that the sample contains 28.5% organic matter. Also, the total organic carbon and total inorganic carbon are 19.71% and 5.83%, respectively. Due to its low H/C (1.26) and high O/C (0.09) molar ratio, kukersite oil shale can be classified as Type II oil shale.

Table 1 Elemental and proximate analysis for the oil shale and the organic matter in the oil shale

Elemental analysis		
	Dry basis, wt %	Organic matter, wt %
C	25.54	69.1
H	2.38	8.3
N	0.06	0.2
S	1.73	2.1
Cl	0.15	0.5
O	18.69	19.8

Proximate analysis	
Volatile matter	31.36%
Moisture content	0.44%
Ash content at 950°C	51.59%
Fixed carbon	16.61%
Lower heating value	8891.5 J/g

Table 2 presents the yields from Fischer Assay under N₂, CO₂ and also with injected steam. Since the yield of liquid products from the tests were small, it was not possible to separate the oil and water. The results are the average of at least two tests for each test atmosphere. The variation of values for parallel measurements did not exceed 10%.

Table 2 Fischer assay yields under all test environments

Dry oil shale basis, wt%	N ₂	N ₂ /steam	CO ₂	CO ₂ /steam
Oil+Water	15.9	17.2	16.1	17.4
Gas	6.7	7.8	6.8	7.6
Semicoke	77.3	75.0	77.1	75.0

As can be seen from the table, the liquid and gas yields increased when steam was injected along with the sweep gases. EL Harfi et al. [24] suggested that steam enhances oil evaporation and decreases coke formation. In addition, injection of steam caused more mass loss in the sample. The loss could be a result of reactions between water vapor and the oil shale organic matter. These results agree with the findings from other studies [24], [25]. Furthermore, water vapor speeds up the process of vaporization, desorption and diffusion of low molecular weight components in the pores by breaking their bonds with the macromolecular part and separating them as volatiles [26]. Other researchers have also studied the effect of steam as a sweep gas in pyrolysis. Williams and Nazzal [27] pyrolyzed oil shale in a fixed bed reactor from 400-620°C under nitrogen and nitrogen/steam atmospheres and found that the presence of steam increases the oil yield significantly at all temperatures. For instance, at 520°C and using nitrogen the liquid yield was 11.84%, whereas the presence of steam increased the liquid yield up to 13.89%. Steam enhances the liquid yield by preventing retrogressive reactions that lead to char formation, probably via dehydrogenation of alkanes to alkenes and cyclization [28].

Oil properties

Table 3 presents the elemental composition of the derived oils. The results show that the elemental composition for all oils is similar. It can be seen from the table the nitrogen content is lower when steam was added to the retort. This is because the nitrogen is contained in aromatic molecules of the

oil and these molecules, because of their higher stability, are resistant to thermal cracking [29]. Thermodynamically speaking, aromatic compounds are more stable than aliphatic compounds. So, when cracking reactions increasingly take place, aliphatic compounds - which at high temperature undergo gas phase cracking - are converted to low molecular weight hydrocarbons. As a result, oils with more aromatic compounds are produced. Hence, aromatic nitrogen compounds are selectively concentrated [27], [29]–[31]. On the other hand, other researchers also reported a similar result and proposed that the reduction of nitrogen content could be a result of steam ability to react with part of the organic nitrogen [32]. They also linked this occurrence with the ability of steam to recover the very light fractions which are low in nitrogen [33]. Furthermore, it is apparent that injection of steam increases the atomic H/C ratio. The H/C ratio is helpful to identify whether the oil sample is aromatic- or aliphatic-rich [34]. In general, a lower H/C ratio indicates that the produced oil contains more aromatics compounds [27], [28], [30]–[32]. A decrease in H/C ratio could be as a result of decrease in long-chain alkanes and increase in alkenes and aromatic content [35]. Furthermore, Olukcu also reported that using water vapor as the sweep gas results in a higher production of aliphatic hydrocarbons in the derived oils [36]. According to Basu, introducing steam increases the H/C ratio, resulting in more gaseous products and less solid char [37]. Table 2 also shows that more gas was produced under pyrolysis in the presence of steam.

Table 3 Elemental analysis on derived oils

Oil Sample	N [%]	C [%]	H [%]	S [%]	O [%]	H/C
N₂	0.18	81.30	9.35	0.84	8.33	1.380
N₂/steam	0.13	82.78	10.10	0.88	6.11	1.464
CO₂	0.18	80.84	9.35	0.85	8.78	1.387
CO₂/steam	0.14	83.75	10.11	0.8	5.29	1.448

Table 4 shows the molecular weight, density and refractive index measured for the produced oils. Several researchers found that the oil from pyrolysis with steam contains lighter hydrocarbons. This may be a result of enhancement of secondary reactions with steam. This is due to the reaction with carbon and the catalyzing effect that some minerals have. They also suggested that water vapor speeds up the process of desorption of low molecular weight products from the mineral matrix [24], [25], [38]. Furthermore, steam aids evaporation of the oil and decreases coke formation [39].

Table 4 Molecular weight, density and refractive index measurements of produced oils

Fischer assay test	MW (g/mol)	Density @15.6 °C (g/cm ³)	Density @20 °C (g/cm ³)	RI @ 589.3 nm
N₂	290	0.9698	0.9661	1.5349
N₂/steam	282	0.9788	0.9749	1.5394
CO₂	283	0.9769	0.9730	1.5372
CO₂/steam	278	0.9776	0.9737	1.5369

Järvik and Oja [40] studied the shale oils from four different deposits produced using a modified Fischer assay method and suggested that the average molecular weight for the Fischer assay oils is about $279 \pm 26 \text{ g.mol}^{-1}$. They also narrowed down the range further to $290 \pm 13 \text{ g.mol}^{-1}$ for high yield oil shales and also suggested that oils with a higher aliphatic content (or oils with higher H/C) tend to have higher molecular weights. William and Nazzal [30] also measured the molecular weight of pyrolysis oils in the temperature range of 400–620 °C and reported that an increase in pyrolysis temperature lowers the MW range of the oils. They attributed the reduction in MW range to an increase in the concentration

of aromatic compounds and a lower concentration of higher MW aliphatic compounds when the temperature increases.

TGA and DSC analysis

TGA and DSC were performed to study the behavior of thermal decomposition of oil shale kerogen when the temperature is increased. Figure 1 shows the mass loss behavior of kukersite oil shale in N_2 and CO_2 as a function of temperature. It can be seen from the figure that at temperatures below 200°C only a little weight loss occurred, mainly due to the evaporation of moisture. Below 350°C the mass loss is small and almost identical for both. However, above 350°C the process of pyrolysis largely begins with mass loss at a higher rate. This happens due to the decomposition of organic matter and continues up to 520°C, at which point most of the hydrocarbons have been released.

Figure 1 TGA curves of Ojamaa oil shale in N_2 and CO_2

As shown in the figure, the weight loss in the CO_2 environment was observed to be larger in comparison with N_2 even though, this difference is not significant. Also, this small difference at low temperatures could also be a result of heterogeneity of the sample. Jaber and Probert suggest that the presence of alkali metals - which play a role in carbon dioxide and H_2O reactions with carbon – cause higher reactivity in CO_2 , and thus, a higher mass loss [15]. This result matches other work given in the literature [15], [16], [41], [42].

In order to create conditions similar to the Fischer assay tests, TGA tests were also run with the injection of steam so that the effect of water vapor on weight loss could be studied as well. Figures 2 and 3 illustrate the results for the oil shale sample in the presence of steam. As can be seen, more mass loss was observed after injection of steam into both environments. Also, despite almost identical mass loss rates, steam seemed to shift the pyrolysis process to a lower temperature than the test without steam. Additionally, running TGA tests under N_2 /steam and CO_2 /steam atmospheres increased the weight loss by about 2% and 3%, respectively.

Figure 2 Comparison between the TGA in N_2 and N_2 /steam

Figure 3 Comparison between the TGA in CO_2 and CO_2 /steam

Figure 4 compares the DSC curves obtained for oil shale under CO_2 and N_2 and both curves show similar trends in general. As the temperature increased to 150°C, endothermic behavior can be seen from the curves as heat is required to evaporate water particles from clay minerals [43]. At about 200°C, the process of conversion of kerogen to bitumen starts by softening and changing the molecular structure of kerogen. This is followed by the release of gases as well [15]. Subsequently, from 200°C to 500°C, thermal decomposition of kerogen to bitumen and then to oil and gas can be seen as an endothermic peak. Also, the figure shows that the slope for the CO_2 run continuously increased until the end of the

decomposition process while for N_2 it started with a moderate slope which seems to be the releasing of light organic content up to 200°C and then a sharp increase for N_2 took place from 350°C . After pyrolysis, or after the pyrolysis peak temperature (around 450°C), the heat requirement reduced which means some material the pyrolysis is completed. In general, comparing the DSC results indicate that both curves behave similarly and the thermal decomposition is not affected by the carrier gas.

Figure 4 DSC curves for the oil shale sample under CO_2 and N_2

Fourier-transform infrared spectroscopy (FTIR)

FTIR spectra of the shale oils produced in CO_2 and N_2 atmospheres are shown in Figure 5. From the figure it can be seen that the spectra are relatively similar for both samples. The highest peak area is within the band range of $2750\text{--}3000\text{ cm}^{-1}$, which is indicative of the aliphatic C-H functional group in the oil. In addition, two distinct differences can be seen between the curves at wavenumbers of $700\text{--}1800\text{ cm}^{-1}$ and $3200\text{--}3600\text{ cm}^{-1}$. The former range can be used to mainly characterize C-H bonds and obtain information about the aromaticity and chain length. More specifically, absorptions for methyl C-H (CH_3 at 1365 cm^{-1}), methylene and methyl groups C-H (CH_3+CH_2 at 1465 cm^{-1}), aromatic C-H bonds including CH out-of-plane bending; solo, duet, trio and quartet ($700\text{--}900\text{ cm}^{-1}$) as well as C-H in-plane bending ($950\text{--}1225\text{ cm}^{-1}$) can be observed within this region. Two bands at 1500 cm^{-1} and 1600 cm^{-1} are ascribed to aromatic ring vibration and the presence of a weak band at $3000\text{--}3150\text{ cm}^{-1}$ confirms their assignment. Also, the region $3200\text{--}3600\text{ cm}^{-1}$ is assigned to the presence of O-H functional groups [44], [45].

The figure shows that the intensity of the absorbance peaks in the regions $700\text{--}1000\text{ cm}^{-1}$ as well as that of the hydroxyl groups band is significantly lower in CO_2 than N_2 . This suggests that CO_2 enhanced the cracking of hydroxyl groups and converted them into volatile matter [46]. Also, it can be seen that the intensity of aliphatic peak at $2750\text{--}3000\text{ cm}^{-1}$ for the oil from CO_2 pyrolysis is higher, whereas the

oil from N₂ pyrolysis showed bigger peaks in the aromatic regions. This indicates that using CO₂ as the carrier gas produced a more aliphatic oil. The higher aromatic peak under N₂ may be a result of the selective concentration of existing aromatics and aromatization of aliphatic compounds in the shale oil [47].

Figure 5 Infrared spectra of the oils produced in a Fischer assay under CO₂ and N₂

Figure 6 Comparison between the FTIR results for the Fischer assay oils in N_2 and N_2 /steam

Figure 7 Comparison between the FTIR results for the Fischer assay oils in CO_2 and CO_2 /steam

Figures 6 and 7 show the spectrum of oils produced in the presence of steam. It seems that the presence of steam did not markedly affect the intensity of the hydroxyl group bands for both environments; however, the aliphatic peak slightly increased for the oil under N_2 when steam was added. By contrast, steam significantly decreased the aliphatic peak in CO_2 . Furthermore, looking at the band region $700\text{--}1700\text{ cm}^{-1}$, the band for N_2 is noticeably higher than that of in N_2 /steam. On the other hand, steam significantly reduced the intensity of the alkenes and aromatic C-H bonds peaks in

N₂ oil, whereas for CO₂, steam had slight effect on these chemical structures in the oil. The aliphatic peaks of the spectra in both figures indicate an inverse effect of steam in N₂ and CO₂. The figure shows that the presence of steam in CO₂ reduced the aliphatic peak of the oil, which is the opposite of N₂ where steam caused a little increase in the aliphatic peak. William and Nazzal [48] concluded that formation of aromatic compounds during pyrolysis is due to secondary reaction in which gas-phase cracking of long-chain aliphatic compounds leads to conversion to low molecular weight hydrocarbons. Carter and Taulbee [33] also suggested that an increase in oil aromaticity is a result of an increase in secondary reactions, which is caused by an increase in bed temperature. Burnham and Happe [49] proposed a mechanism for the conversion of aliphatic and aromatic content to oil, gas and carbonaceous residue. They expressed that during pyrolysis both aromatic and aliphatic structures in kerogen play a role in producing aromatic oil, and some of this oil is subsequently converted to coke. However, the main difference between these two kerogen portions is that the aliphatic content of kerogen is converted to aliphatic oil and gas while the aromatic content of kerogen has more of a tendency to remain in the char. On the other hand, during oil vapor cracking, some of the long-chain aliphatic structures are converted to short-chain alkanes and alkenes as well as gas, which results in the production of hydrocarbons with a lower carbon content [47]. But, the aromatic carbon in oil shale remains greatly unaffected by thermal decomposition, which means they have a higher tendency to become carbon residue [50]. Therefore, it can be perceived that during thermal cracking, aliphatic compounds are transformed into aromatic compounds. This may be the primary reason that the amount of aromatic carbons in the recovered oil and solid residue is higher than that in raw oil shale: aromatization of aliphatic carbons. Accordingly, the process of conversion of aliphatic to aromatic is considered to have undesirable effect on generation of oil and thus inhibits achieving high oil yield [51], [52].

Conclusion

In this study, Estonian kukersite oil shale was pyrolyzed using the Fischer assay method under N₂, N₂/steam, CO₂ and CO₂/steam environments. The results showed that the presence of steam in both environments produced more liquid and gaseous products. Also, injection of steam caused an increase in mass loss in comparison with the tests without steam and this loss was greater in the CO₂ atmosphere. In addition, oils produced under all environments had similar properties. However, the FTIR results indicated that the chemical structure of the derived oils was affected to some extent depending on the environment used. Overall, analysis of the oils from pyrolysis shows that at low temperatures CO₂ retorting and N₂ retorting yield oils with fairly similar characteristics. Though, according to the results obtained from TGA, using CO₂ as the sweep gas could possibly increase the shale weight loss, which means more of oil shale is converted into hydrocarbons. Comparing the results with the test in N₂, CO₂ seems to produce more liquid products, even though the difference is slight. This was reported previously by several researchers as well. In addition, over the studied temperature range, the effect of steam seems to be considerable. Injection of steam along with the sweep gas produced oils of a higher quality. That is due to the fact that steam increased the H/C ratio and also reduced the amount of nitrogen and oxygen atoms. Steam did not show remarkable impact on sulfur content of shale oil, however. As mentioned earlier, due to the higher availability and low cost of N₂, using nitrogen as carrier gas has been extensively studied and discussed. Conversely, the number of research works on pyrolysis of oil shale in a CO₂ atmosphere is not large. Current results available in the literature on using CO₂ as a sweep gas has been indicating promising results in terms of improving the quantity and quality of the derived oils. As seen in the results, CO₂ is one of the main components of pyrolysis gas. Furthermore, using CO₂ is known to have environmental impact as well. Therefore, the feasibility of development of recycling and utilizing CO₂ produced from oil shale pyrolysis could possibly be an attractive way to mitigate the emission of CO₂ to some extent and also to make its usage

more economically viable. Consequently, with reference to previously stated points - chemical changes to the products, environmental issues, potential economic benefits – the products from pyrolysis in CO₂ may be of interest to corresponding industries.

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