

Article

Comparative Analysis of Partially Renewable Composite Fuels Based on Peat, Lignite and Plant Oil

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Abstract: The inevitable depletion of exploited fossil fuel deposits motivates the investigation of every possibility of saving them. One of the ways to do that is to combine fossil fuels with renewable plant-derived fuels. This paper studies the specific aspects of the thermochemical conversion of composite fuels consisting of peat or lignite with rapeseed oil. It was shown that mixtures of peat or lignite with rapeseed oil can be successfully gasified when the temperature is higher than 700–800 °C. The self-sustaining combustion of these fuels does not support such high temperatures, and thus the process requires external heating. The obtained optimal component ratio for peat-oil and lignite-oil compositions is about 1:2 and 3:2, respectively. Such mixtures allow the most efficient usage of the oxidation heat during conversion. The high calorific value of such fuels is very close to that of rapeseed oil (38.5 MJ/kg), even for the lignite-oil composition with 40 wt% lignite. Lower overall prices of fossil fuels compared to pure renewable plant-derived fuels help reduce costs and save valuable fossil fuels.

Keywords: low-grade fossil fuels; rapeseed oil; fuel composition; thermochemical conversion; allothermal process

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1. Introduction

Recent increases in the traditional energy resource prices have sparked a considerable interest in alternative fuels [1,2] as well as in different ways of saving fossil fuels [3]. Many countries have their own deposits of low-grade fuels such as peat (P) and lignite (L). An evident increase in the lignite production and consumption occurred this year in Germany and Poland [4]. The producer price index for lignite shows jumped up to 128% of previous peak values this year [5]. These fuels are less efficient than the ones commonly used in the industry over the last decades, but they are cheap and highly available in different countries [6]. Germany, the Russian Federation, and some others countries have large enough deposits of peat and lignite that can be quickly taken in use. The main problem of low-grade fossil fuels is a smaller calorific value compared to traditional fuels. Variations in the chemical composition of fossil fuels depending on the deposit [7] cause additional difficulties for the industrial application of such fuels. The mineral matter content is up to 40–50 wt%, which leads to big amounts of ash residue. High moisture and volatile content result in a low heating value, slow ignition and an unstable combustion temperature [8]. All these drawbacks make these fuels unattractive for trivial combustion and most of the popular methods of thermochemical conversion. Various approaches to peat pyrolysis and lignite gasification, used over the last few years, show [9–11] that such techniques still need essential improvements.

Another strong trend over the last few years, contributing to lower consumption of fossil fuels, is a growing utilization of renewable fuels [2,12]. Different techniques of plant oil conversion into bio-diesel [12,13] or bio-gas [14] are popular in the modern industry. However, these fuels are quite expensive because of their long growth cycle with large

planting areas and expensive post-processing [15]. This factor has limited the spread of biofuels in industrial use. However, the perspective of the further decrease in oil availability stimulates the interest for bio-diesel and other plant-derived products, even taking into account the three times higher prices of these fuels [16] in comparison with oil. Bio-diesel production requires the thermochemical conversion of aliphatic acids with alcohol (esterification). Effective practical solutions here are compositions of plant aliphatic acids and methanol with a ratio of about 1:10 or even higher [17]. The production of bio-gas with a natural fermentation process looks much easier but it is a slow process. Efficient technologies utilizing this principle require significant investments in infrastructure located over large areas. Different processing techniques allow the production of biofuels with higher energetics or better ecological indicators [18]. Different pre-treatment approaches allow an essential enhancement of the availability of lignocellulose for hydrogen production [19].

A special way of involving renewable components is the preparation of partially renewable fuel compositions [20,21]. Plant oils can be easily mixed with low-grade fossil fuels to produce new compositions whose properties are quite appropriate for applications. Some co-firing approaches [22,23] show a great potential of decreasing hazardous emissions as well as a rather high level of energy efficiency. The usage of the peat as a sorbent for spill oil shows the good potential of composing it with different aliphatic acids [24].

Mixing fossil fuels with renewables can extend the application area of low-grade fuels and make renewable fuels cheaper. The main task in this field is to determine the component ratio and thermal regime for the efficient use of a composite fuel that allows maximal production of combustible gases. Plant-derived aliphatic acids require rather high temperatures for efficient conversion [25]. There are much fewer investigations into the high-temperature co-conversion of biomass and fossil fuels than there are into co-firing. The fossil fuel has higher reactivity at low temperatures in comparison with rapeseed oil (RO) and can serve as a booster for oxidation of composite fuel. Effective conversion of such composite fuels requires fast heating to temperatures high enough for the thermal degradation of aliphatic acid and, thus, represents a more complicated task compared to ordinary combustion.

Thermochemical conversion of compositions consisting of plant oils and peat is poorly reviewed to the moment. These compositions look promising because the usage of widespread components, which are cheap (peat, lignite) or have a high combustion heat (rapeseed oil). The synergistic effect of the right combination of them potentially allows making cheap quasi-renewable fuel. The potential application of the produced gas can cover a wide area, from the heating purposes of small households in villages equipped by solar assisted conversion reactors to the gas supply chemical synthesis facilities.

The problem of co-conversion of low-grade fossil fuels and plant-derived oils is poorly investigated. The biogenetic conversion described in [26] is a long-time away. Thermal conversion can be a faster alternative. Permanent increases in oil prices shows that oil usage will go down in future. Agricultural combustible products already took oil's place in some applications. It is reasonable to estimate that this trend will continue in future. Development of the approaches that are appropriate for the usage of compositions of plant oils is a desirable step forward for fuel related science.

The goal of this study is to analyze the oxidation dynamics of composite fuels (made of rapeseed oil with peat or lignite) in a wide temperature range. Another important point is to determine the dependence of the gas product composition on the temperature and fuel component ratio. New data were presented about the optimal component ratio for the maximal yield of combustible gases. The oil fraction threshold that almost stops the gasification process was determined. Thus, the overall novelty of the presented results is in the demonstration of the effective compositions of quasi-renewable fuels suitable for thermochemical conversion under high-power radiative heating by focused visible light at atmospheric pressure.

2. Materials and Methods

The compositions of peat and rapeseed oil (P + RO) were prepared using the peat from the Sukhovskoe peat deposit of the Tomsk Region, Russian Federation [27]. B2-class lignite from one of the deposits of the Krasnoyarsk Region, Russian Federation was used to prepare the compositions of lignite and rapeseed oil (L + RO). The properties of solid components are summarized in Table 1. One can see that these fuels have essential differences in moisture and ash content as well as in the amount of volatiles and in the chemical composition. The heat capacity and calorific value of lignite are a bit higher than those of peat, whereas the heat conductivity and thermal conductivity of lignite are lower.

The technical grade rapeseed oil produced in the Tomsk Region, Russian Federation was used as a renewable component of the compositions. The properties of the RO are shown in Table 2. The data were obtained from the specification of the oil manufacturer that correlated well with earlier published data [28].

The solid components (peat and lignite) were milled by a rotary mill and riddled through calibrated sieves. Thus, the average particle size was about 100 μm . The obtained powder was mixed with RO according to the required component ratio. The resulting composition was mechanically mixed by a rotary homogeniser for 10 min. Such mixtures keep good enough homogeneity, even in millimeter size droplets. The sample weight for the thermogravimetric analysis (TGA) investigations was about 5–6 mg. The sample weight for calorimetry was about 0.6 g. The sample weight for the allothermal gasification was about 0.5–1 g.

TGA estimates the most optimal thermal regime for the thermochemical conversion of the fuel under study. It was performed using an SDT Q600 analyzer. The thermo-gravimetric measurements were performed at an air feeding rate of about 2 mL/min and a temperature increase rate of 10 K/min.

Table 1. Properties of solid components of the fuel composition [29,30].

Property	Lignite	Peat
Moisture, wt%	14.11	38.2
Ash content, A_d , %	4.12	31.5
Volatile content, V , % (daf)	47.63	71.5
Chemical composition, wt% (daf)		
C	73.25	51.03
H	6.516	6.01
N	0.79	4.62
S	0.435	0.15
O	18.99	38.19
Thermal properties		
Heat conductivity, λ , W/(m·K)	0.15	0.22
Heat capacity, C_p , kJ/(kg·K)	2.09	1.77
Thermal diffusivity, a , cm^2/s	0.007	0.01
High combustion heat, Q_{as} , V , MJ/kg	22.91	19.4

Calorimetry was performed with an ABK-1V Bomb Calorimeter.

The gasification of composite fuel was carried out using an original technique [9,22], with samples exposed to radiative heating by a focused flow of visible light (see Figure 1). The 500 W halogenic lamp provided a white light flow with a power of up to 15 W. Focusing the flow with a parabolic mirror to the spot about 1.3 mm in diameter allowed the intensity of the radiation of up to 1 kW/cm² (which was controlled by a thermoelectric power meter). The light flow intensity was adjusted by varying the electrical current in the lamp circuit.

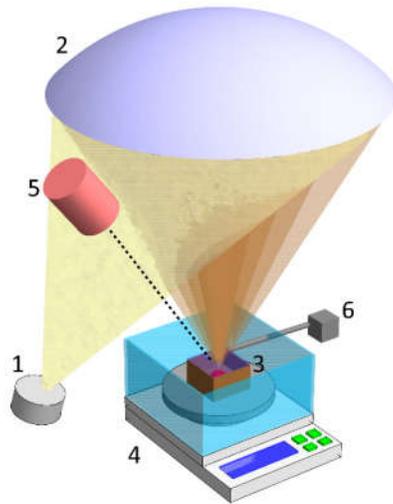


Figure 1. Scheme of the experimental setup for high-temperature gasification of the fuel under a light flow. It includes a light source (1), a parabolic mirror for light focusing (2) and a cuvette with fuel (3) placed on an electronic balance (4) platform. The gas analyzer (6) is connected to the cuvette with a quick connect fitting. The thermal imaging system is (5).

The fuel sample was placed inside a chamber with an optical window on the top. The radiative heating of the sample was carried out through this window with a simultaneous measurement of the temperature of fuel surface by an Optris Pi 1 M thermal imaging system. The emitted gases were pumped out from chamber through a fitting at the sidewall of the cuvette by a gas analyzer pump. The oxygen income went through the slit in the opposite wall of the chamber. The performance of the pump of gas analyzer was about 4 mL/s.

Table 2. Properties of rapeseed oil.

Chemical Composition, wt%:	
C	78
H	10
O	12
S	<0.01
Physical Properties	
Density at 15 °C, kg/m ³	897
Lower calorific value Q_p , MJ/kg	36.99
Cetane number	41
Flash point determined in a closed cup, no lower than, °C	109
Pour point, °C	-16

The chemical composition of the gases produced was analyzed using a Test-1 gas analyzer. It allowed the real-time monitoring of the volume concentrations of the CO, CO₂, CH₄, NO_x, SO₂ and H₂, with measurement errors of less than 10%. The gases were dried and cooled to room temperature before the analysis.

The sample weight changes with time during the gasification process and, additionally, measured using the electronic analytical balances (with disconnected gas flow pipes). Thus, the employed techniques make it possible to compare some important parameters of the composite fuel conversion for different fuel compositions.

All gasification experiments were repeated five times for the minimization of the random errors. The presented confidence intervals were estimated using a 90% confidence probability.

3. Results and Discussion

3.1. Reactivity of the Composite Fuels

The dependence of the fuel reactivity on the temperature was estimated using the TGA technique. The obtained dependencies for pure peat, pure lignite and rapeseed oil were compared with the curves describing the thermal decomposition of the mixtures: P + RO (35 wt% and 65 wt%) and L + RO (60 wt% and 40 wt%). These particular compositions were chosen following the previous investigations [16] as well as because of the results presented further in Section 3.3. Figure 2 shows the TGA results.

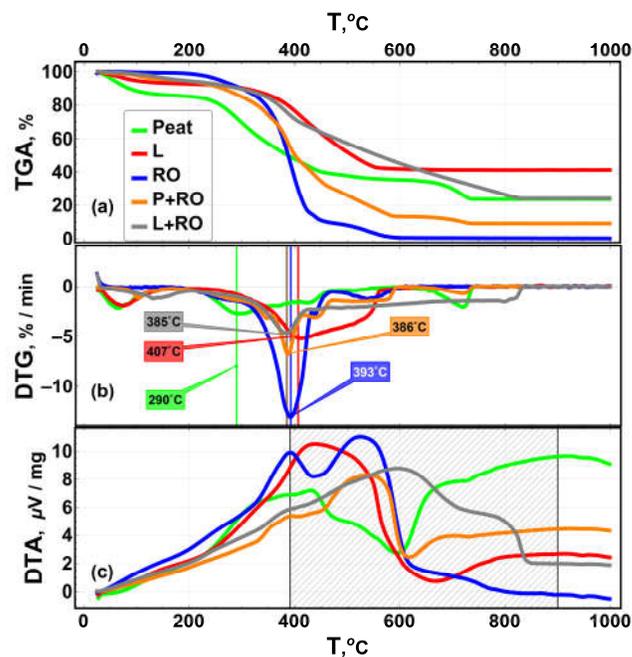


Figure 2. TGA results for thermal decomposition of fuels. TGA dependencies (a), the DTG dependencies (b) and the thermal effect of fuel decomposition (c). The shaded area on the plot shows the temperature range where the maximum heat production is recorded for all the fuels.

With the desired oxygen flow, one can estimate the temperature ranges that correspond to the most effective decomposition of the organic part of the fuel. According to the chemical compositions of our fuel components (Tables 1 and 2), the minimal amount of an air needed for full oxidation of the fuel compositions (for sample weights used for TGA) is about 45–50 mL. In contrast to the pure peat and lignite, which require different amounts of air (29 mL and 45 mL) for full oxidation, the compositions (L + RO and P + RO) require a very close amount of oxidant. Taking into account the effective fuel oxidation range (from Figure 2) and the chosen air feeding regime (2 mL/min), the average coefficient of excess air is less than 1.5 for the L + RO mixture and about 0.9–1 for the P + RO mixture. Thus, the oxidation conditions are suitable for gasification process. The experimental setup shown in Figure 1 provides a similar air excess coefficient for bigger fuel portions.

One can see that the weight losses curves (TGA) for the fuel compositions mostly lie between those for single components, similar to Ghaly et al. [31]. However, the differential thermal analysis (DTA) shows a significant shift in the extensive heat release right along

the temperature axis for the composite fuels (relative to the heat release of the fuel components). At the same time, mixing RO with peat makes the TGA curve slope steeper in the temperature range where the most effective decomposition occurs (300–600 °C).

The reactivity peaks of pure components (peat, lignite and RO) occur at 290 °C, 407 °C and 393 °C, respectively. The P + RO and L + RO compositions have maximum weight changes at approx. 390 °C. Thus, this temperature appears to be the lowest conversion threshold for such compositions (Figure 2b). It is clear that conversion is most effective at higher temperatures. In the considered case of conversion under a focused light flow, the temperature is always close to 700–800 °C or even higher. At the same time, all the chemical reactions and other processes (such as drying) proceeded separately at lower temperatures, starting at this point, simultaneously, during the rapid heating to high temperatures (within several seconds).

The analysis of the heat of reaction (Figure 2c) shows that the heat production peaks during the thermal decomposition of the composite fuels that occurs at higher temperatures than for pure peat, lignite or RO. One can see that the DTA curve maximum for the L + RO mixture occurs at about 600 °C. The P + RO mixture produces maximal heat at about 550 °C. The presence of a slight drop in the blue curve near 450 °C reflects the effect of the evaporation of the volatiles from the RO. The above suggests that the stable self-sustaining ignition of P or L filled with big amount of RO is almost impossible (it requires very intensive external heating). The reason for that is that the fuel self-heating is very weak in the maximum reactivity range. The combustion of these compositions cannot proceed without external heating, maintaining fuel temperatures above 600 °C. When the heating intensity is low (for example, during peat smoldering), oil takes a long time to evaporate. This keeps the temperature moderate until the moment when most of the oil is released. The synergistic effect of the simultaneous oxidation of different fuel components will be lost in this case.

A high-power external light source heats the fuel to temperatures of about 550–600 °C in 2–3 s, and thus it effectively involves the fuel oxidation heat in the conversion process. The common approaches to fuel combustion in a furnace [4,10], where the heat flow intensity does not exceed 100 W/cm², do not allow the real co-firing of fossil fuels with rapeseed oil. In this case, a significant part of the fuel can be involved in the reaction only after a certain part of the volatile content of the oil evaporates [22,31].

3.2. The Conversion Temperatures and Oxidation Heat

It is well known that temperature is one of the decisive factors of fuel conversion [11]. The focused light flow quickly increases the temperature of the lit surface of fuel to the steady state value that is defined by both external heating and the chemical reaction heat inside the fuel layer.

The trend in the average conversion temperature versus a wide range of oil fractions in the fuel composition is shown in Figure 3. One can see that an increase in the fraction of RO in the P + RO composition leads to a slight increase in the process temperatures followed by a decrease (after 45 wt% of RO). An equivalent dependence for the L + RO compositions shows the peak temperature at about 35 wt% of RO. The subsequent decrease in temperature (within the red zone) is accompanied by an increase in the conversion duration (for the fixed weight of fuel sample). It increases 2–3 times in the case of 0.35P + 0.65RO compositions relative to the conversion time of pure peat. Similarly, the conversion of 0.6L + 0.4RO proceeds 1.3 times longer than that of pure lignite.

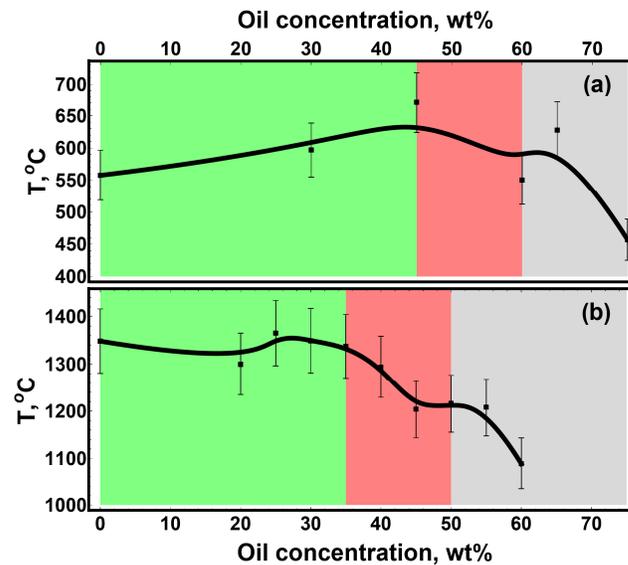


Figure 3. Average temperatures during conversion for P + RO (a) and L + RO (b) fuel compositions. The red zone corresponds to fuel conversion. The green and gray zones correspond to compositions with excess production of CO₂ and extremely low overall gas production.

Thus, the red area shows the optimal oil concentration range where the overall heat production through conversion is close to maximum (the temperature decrease is compensated by increased duration of heat production).

The green areas correspond to the regimes with excess CO₂ production. The gray areas correspond to the fuel with an evident excess of RO, where the intensity of gas production is very weak. This occurs because the external heating power is not enough to keep the temperature of around 600 °C during the rapid evaporation of the volatiles.

Figure 4 shows the results of the calorimetric analysis (red diagram) and the peak temperatures (green) observed during the light-induced allothermal conversion of fuels (using the setup from Figure 1). One can see that the maximum temperature was recorded in the conversion of pure lignite (~1300–1400 °C). The lowest peak temperatures were recorded during the conversion of pure rapeseed oil and pure peat. However, the P + RO composition shows a higher temperature. This indicates that the heating is enhanced due to the interaction of the fuel components. The L + RO composition shows a certain decrease in the conversion temperature relative to the maximum possible one for lignite. At the same time, the L + RO mixture features higher conversion temperatures combined with a higher consumption of fossil fuel.

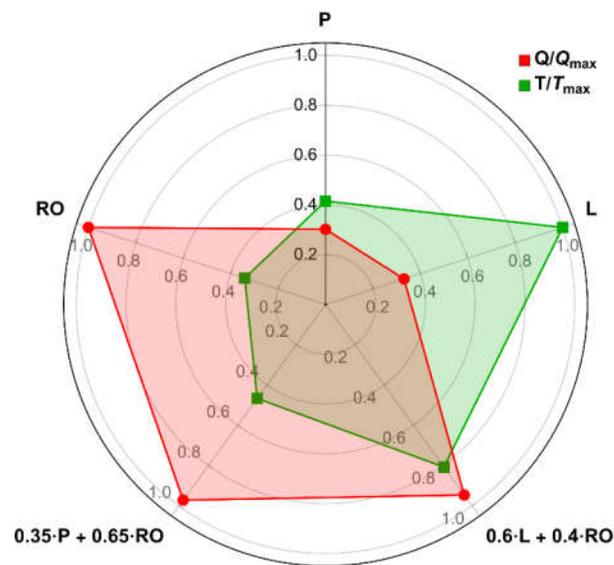


Figure 4. Characteristic temperatures (green) recorded during the allothermal conversion of composite fuels and their components (normalized to the highest temperature) and high calorific values of the fuels (normalized to the highest value). Normalization factors: $T_{\max} = 1350$ °C, $Q_{\max} = 38.5$ MJ/kg.

The P + RO mixture contains much more oil per unit weight than the lignite-based one does. However, their calorific values are quite similar. The peat oxidation appears to slowly smolder, whereas lignite oxidizes much faster.

The high calorific value obtained for pure RO was 38.5 MJ/kg. All the compositions containing a considerable amount of RO featured quite high calorific values too. Pure peat and lignite have a much lower calorific value due to the presence of mineral matter and certain moisture. It is clear that the high calorific values measured for the composite fuels differed greatly from the estimations obtained using the common additive relations (0.6 and 0.76 for the L + RO and P + RO compositions, respectively). This is especially evident for the P + RO mixture. This composition has a very attractive heat of combustion with a very high fraction of renewables. This result correlates very well with earlier reported data [31] about high calorific value of diesel-contaminated peat. The corresponding high calorific value was reported at about 36.79 MJ/kg (sample C). One can see that an increase in the amount of rapeseed oil reduces the peak temperature, despite the solid component used. However, the high calorific value of the composition increases with the increasing oil fraction.

Finally, the calorimetric analysis shows that the high-temperature combustion of the L + RO and P + RO compositions provided a very high heat of combustion. The self-sustainable combustion of such fuels at lower temperatures (without external heating) was accompanied by very long ignition delays when a considerable part of the volatiles was released before the fuel ignition [32].

3.3. Composite Fuel Gasification Products

The optimal composition of peat or lignite with rapeseed oil can be determined by considering the variations in the gasification products versus the component ratio of the fuel. Gasification (see Figure 1) proceeded with external heating (the intensity of the light flow to the fuel surface was about 880 W/cm²), and the fuel temperature typically reached maximum values within a couple of seconds. Such external heating allowed for fuel temperatures as high as 500–600 °C without the contribution of the heat of the reaction (e.g., in a nitrogen atmosphere).

It is clear in Figure 5 that the overall gas production goes down with an increase in the fraction of RO. The concentrations of the gases under study were obtained here by using integral averaging throughout the process.

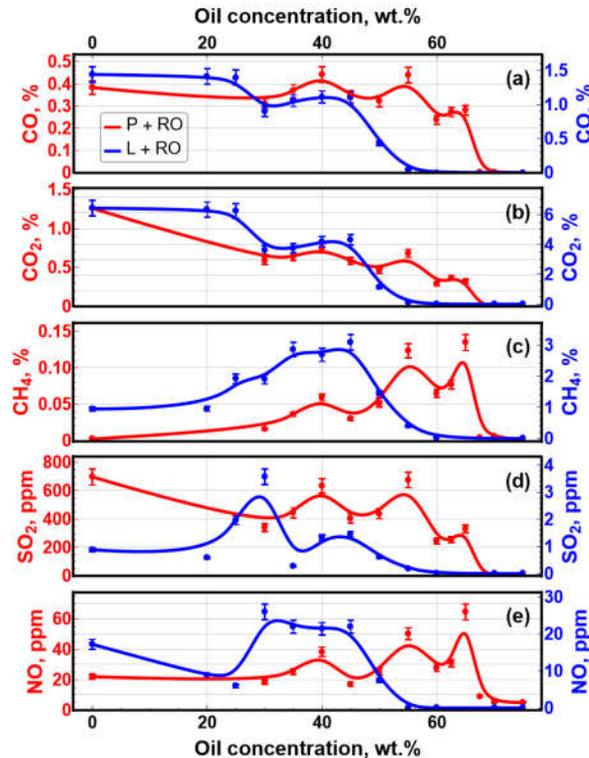


Figure 5. Chemical composition of producer gas for different fossil fuel–renewable component ratios in the composite fuel. The gas trends are shown in subfigures: CO (a), CO₂ (b), CH₄ (c), SO₂ (d), NO (e). The optimal fuel compositions are 35 wt% peat and 65 wt% rapeseed oil; 60 wt% lignite and 40 wt% rapeseed oil.

The production of almost all the considered gases was maximum in the conversion of the P + RO mixture (35 wt% and 65 wt%). A similar extremum was recorded in the conversion of the L + RO mixture with 40 wt% RO. Thus, these particular compositions look optimal in terms of combustible gas production. The production of combustible gases exceeded that of non-combustible ones by 10–15% in the case of the optimal fuel composition.

The gas production intensity was higher in the conversion of the L + RO mixture because of much higher temperatures of this process (see Section 3.2). However, when the oil fraction was increased above the optimal level, the process quickly decayed. It occurred due to the enhanced evaporation of the volatile components of oil, as well as due to the heat-consuming oil pyrolysis. Lower heat production due to the oxidation of a smaller amount of the fossil fuel component goes in parallel with an increase in the RO fraction.

The analysis of the chemical composition of producer gas obtained for fuel compositions with different oil fractions showed the presence of an evident peak of combustible gas production (red curves in Figure 5a,c) when the peat-oil ratio was about 1:2. This fuel contained about 67 wt.% renewable component. The optimal lignite-based composition contains 40 wt% renewables. Thus, the proposed approach paves the way for fuels with a rather low content of fossil fuels and a lower price compared to fuels involving only renewable resources or pure plant oils.

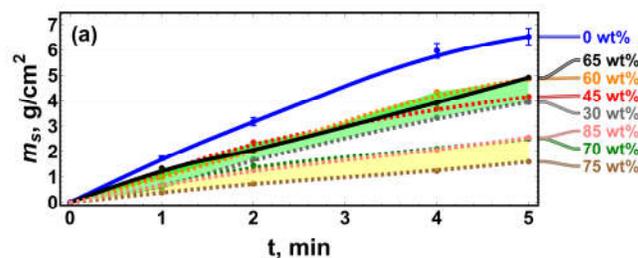
In contrast to the traditional gasification techniques, the proposed approach allows the fuel conversion at normal pressure when most of the energy is obtained from the external source through the high-power radiation flow. These differences of process conditions determine the specific aspects of the presented conversion regime, such as an absence of a great amount of hydrogen typical of high-pressure conversion [33] or different biomass conversion methods [14,34].

Looking at the production of sulfur and nitrogen oxides, one can see that the concentrations of SO_2 in the conversion of the optimal P + RO composition are twice as low as in the conversion of pure peat. It occurs because the composition contains a considerable amount of oil that does not have sulfur. An increase in the production of NO_x occurs due to the process temperature increase. The chosen conditions of the conversion (excess air ratio of about 0.9) are close to the conditions described in [35] that potentially allowed decreased NO_x production during the conversion of the biomass.

The conversion of the optimal L + RO composition produced 1.5 times more oxides of sulfur and nitrogen relative to the conversion of pure lignite. The reason for that is due to a higher conversion temperature due to a much more effective contribution of oxidation heat in the fuel heating.

In general, some properties of composite fuels (density, heat conductivity, etc.) can be estimated using additive relations, based on the fraction of their components. However, high-temperature processes usually imply the chemical interaction between the composite fuel components [33]. This typically leads to a significant deviation from the predicted trends. The presence of the gas production maximum for certain RO fractions in the fuel composition clearly shows that the interaction of its components during the oxidation is maximal.

The gasification rate of composite fuels with different chemical compositions can be easily estimated from the changes in the total weights of produced gases versus the component ratio. Figure 6a shows the change in the producer gas weight over time in the thermochemical conversion of the P + RO composition. One can see that pure peat (the blue curve) produces the highest amount of gas. It produces more than 6 g of gas per 1 cm^2 of the heated fuel surface. Adding rapeseed oil slows down gasification. The conversion of the composition with 30 wt% RO is twice as slow. However, a further increase in the oil fraction slightly enhances conversion. The maximum gas production occurs when the oil fraction is about 65 wt%. This means that the local maxima obtained earlier (Figure 5) for the production of carbon monoxide and methane are coupled with an overall increase in the gasification rate by up to 80% relative to the conversion of pure peat. A further increase in the RO fraction significantly reduces gas production. The compositions contain 75 wt% rapeseed oil and produce a 6–7 times smaller number of gases, mostly due to the evaporation of the volatile component of RO.



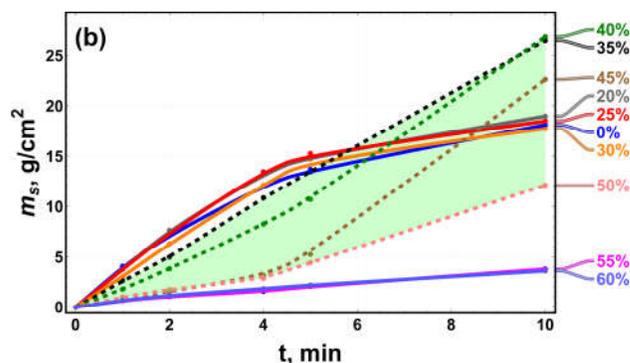


Figure 6. Producer gas weight per square centimeter of the irradiated fuel area versus time. The fuel compositions are P + RO (a) and L + RO (b). The weight fraction of rapeseed oil is shown on the right. The light flow intensity is 880 W/cm^2 .

It is clear in Figure 6b that the conversion of the lignite-based compositions features a much higher overall production rate. Pure lignite can produce up to 15 g of gases per unit area (after 5 min of heating), which is 3 times higher than in the gasification of peat-based fuels.

Adding RO to lignite slightly increases the gas production rate. Moreover, the compositions with 35–45 wt% RO allow a quasi-linear increase in the weight of produced gases over time (after 5 min of heating). Therefore, the maximum production of carbon oxides and methane is up to 25 g per unit area of the irradiated fuel. The overall gas production is maximum when the fraction of RO is about 40 wt%, and it decreases with a further increase in the fraction of RO. Thus, the optimal lignite-to-rapeseed oil ratio is 3:2. The green-colored area in Figure 6 shows the range of the RO concentration that allows quite effective gasification. The yellow-colored area shows the RO concentration range in which only the evaporation of volatiles from the fuel components is possible.

3.4. The Material and Energy Balance of Conversion

The data presented in the previous sections make it possible to determine the expenses of energy consumed from the external source for conversion of the unit weight of the fuel composition. The estimation of the specific energy expenses was performed according following equation:

$$E_{sp} = \Delta E / \Delta m'$$

where ΔE is an energy of absorbed light and $\Delta m'$ is a corresponding weight changes of the sample observed during the time Δt . This value shows the general consumption of the heat from external sources that includes the losses for thermal radiation emitted at the steady state temperature as well as light reflection losses.

The energy needed for the conversion of the unit weight of the L + RO composition was about 9 MJ/kg. The same value for P + RO was about 54.5 MJ/kg. At the same time, lignite produced quite a lot of heat that contributed to the efficient and relatively fast conversion of the L + RO mixture.

The comparison of the findings with the data published earlier on the conversion of a water slurry of peat or lignite [9,11] shows that the conversion of RO-based compositions requires much higher heating intensity (with corresponding temperatures). At the same time, there is also a significant rise in combustible gas production. Both of the proposed compositions provide a considerably better ratio of combustible-to-non-combustible gases than that obtained for the water slurries in [9].

The comparison of the high-temperature oxidation of peat- and lignite-based fuels (Figure 4) shows that both L + RO and P + RO compositions have rather similar high calorific values. However, partial oxidation during the conversion results in very different heat production and different chemical compositions of the producer gas.

The obtained values of energy consumption during the conversion of the L + RO composition are comparable with the ones required for the conversion of the water slurry of bituminous coal processing waste (left three columns in Figure 7) [36]. The samples of coal–water slurry were converted with an air excess coefficient of about 1.3, the value of which is close enough to the conditions of the conversion of the L + RO composition presented in this paper (air excess coefficient ~1.5). The conversion of wet peat or wet lignite usually requires external heating with intensities of about 100 W/cm² [9]. The conversion of wet peat and wet lignite was performed at air excess coefficient of about 1–1.1. The amount of the air moved into the chamber depended on the duration of the conversion process, which was essentially different for all these fuels.

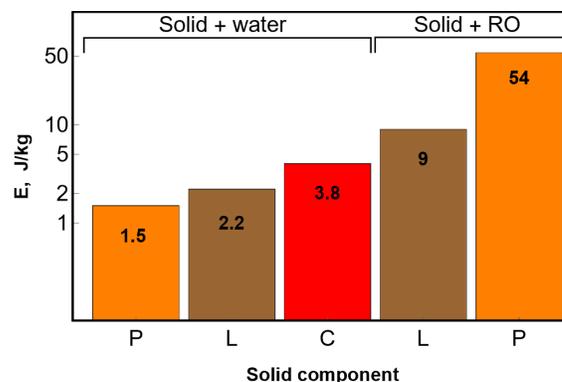


Figure 7. External heating source energy used to convert unit weight of fuel composition. Solid components are peat (P), lignite (L) and bituminous coal processing waste (C). The energy is shown on a log scale.

Figure 7 shows the typical amounts of the externally sourced heat required for the conversion of the unit weight of different fuels. Rapeseed oil makes peat and lignite less sensitive to heating. The oxidation of pure peat or lignite usually goes with increased production of CO₂ at the set heating intensity. However, the chosen P + RO or L + RO compositions increased production of combustible gases instead (see Figure 5).

Therefore, the quasi-renewable composition of lignite (60 wt%) and rapeseed oil (40 wt%) can serve as a cheap and efficient alternative fuel for different industrial purposes. The produced gas mixture has a high calorific value of ~20 MJ/kg (and 10.8 MJ/kg for P + RO). In the case of the L + RO composition, the heating value of fuel gas surpasses the energy invested into conversion process.

Summarizing the previously presented results, we can formulate the appropriate conversion conditions. The conversion of P + RO compositions requires a fuel temperature above 600 °C. This temperature threshold should be achieved in a short time to prevent the separate evaporation of the volatile components of the oil. The effective conversion of L + RO compositions goes when temperature exceeds 1000 °C with similarly fast heating rate.

Comparison of the presented results with already published data about gasification of peat and lignite [21,22,27,31] shows that presence of the RO essentially changes the chemical content of the fuel gas. The absence of noticeable amounts of hydrogen tells us that chemical interaction of the fossil and renewable components shifts more to the methane synthesis. The difference between invested into the conversion process energy and heating value of the fuel gas differs a lot for the L + RO and P + RO compositions. The P + RO compositions with a high fraction of RO require, most probably, stronger external

heating. This potentially can increase the gas production rate and decrease the specific energy expenses. An application of the focused solar light for thermal conversion of the quasi-renewable fuel can decrease the final price of conversion process to practically appropriate values.

4. Conclusions

The quasi-renewable fuel compositions consisting of peat or lignite with rapeseed oil had a high combustion heat comparable with fuel-oil. They could be converted to a mixture of combustible gases using external heating (to more than 700 °C) by the focused flow of visible light. The producer gas contained large amounts of carbon oxide and methane when the weight component ratio of fuel components was 1:2 for the P + RO mixture and 3:2 for the L + RO mixture. These compositions were cheaper than pure rapeseed oil due to the presence of the low-grade fossil fuels (about 40 wt% and more). The lignite–oil mixture can produce gases with a rather high combustion heat, spending about 9 MJ of heat from an external source per kilogram. An application of such quasi-renewable fuels together with solar assisted thermochemical conversion of them can decrease the deficit of the energetic resources for numerous countries that have deposits of peat or lignite complemented with advanced enough agriculture.

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