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The Main Elements of a Strategy for Combined Utilization of Industrial and Municipal Waste from Neighboring Regions by Burning it as Part of Composite Fuels

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Abstract: An experimental study has been conducted into the ignition and combustion processes of composite fuel droplets fed into a heated muffle furnace on a holder. Consistent patterns and characteristics of physical and chemical processes have been established for a group of fuel compositions: wet coal processing waste (a mixture of fine coals and water) 85% + municipal solid waste (wood, or plastic, or rubber) 10% + used oil 5%. Burning a coal-water slurry instead of dry coal dust is characterized by a positive environmental effect. Adding used oil to a coal-water slurry results in better energy performance characteristics of the composite fuel during combustion. Adding fine municipal solid waste (MSW) to the fuel composition makes it possible to effectively recover it by burning in boiler furnaces with energy performance characteristics of combustion and environmental characteristics of flue gases that are as good as those of composite fuel compositions without MSW. Sustainability of the composite fuel ignition process and complete burnout of liquid and solid combustible components have been determined. The values of the guaranteed ignition delay times for droplets with a size (diameter) of about 2 mm have been established for the composite fuel compositions under study in the ambient temperature range 600–1000 °C. The minimum values of ignition delay times are about 3 s, the maximum values are about 15 s under the near-threshold ignition conditions. The obtained findings enabled to elaborate the main elements of the strategy for combined recovery of industrial and municipal waste by burning it as part of composite fuels.

Keywords: municipal solid waste; coal processing waste; oil refining waste; waste management; composite fuel; energy production

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1. Introduction

Nowadays the problem of municipal solid waste (MSW) and industrial waste utilization [1] is very acute in the modern world and the Russian Federation is not an exception. One area of great interest is the design of management systems for waste handling by processing it into energy and valuable products [2]. According to the Russian Federal State Statistics Service [3], about 5441 Mt of industrial waste were produced in country in 2016, which was 7.5% more than in 2015. More than 40,000 Mt of waste have been accumulated in the Russian Federation so far, of which 86% comes from solid and liquid fossil fuel extraction. In terms of the geographic distribution, the Siberian Federal District accounts for the majority of the waste. It makes up about 60% of the total amount of industrial waste in the country.

In 2016, the level of industrial waste recovery was 2685 Mt, or 49.3% of the total volume of its production (Figure 1). The rest of the waste was buried (504 Mt, or 9.3%) or stockpiled at open-air disposal sites for temporary storage (2253 Mt, or 41.4%). Industrial waste disposal sites occupy large amounts of agricultural land, damaging the land cover, soil, and landscape. Moreover, coal industry waste is not only a fire hazard but also contains acid-forming substances, heavy metals, and other elements dangerous for the environment. When exposed to the intensive physical and chemical effects of natural factors (air, water, and solar energy), it becomes a source of integrated pollution of the environment. Coal dust from coal mining and processing pollutes the air and water. Waste containing used oils and petroleum products is toxic. Storing oil waste has the following detrimental effects on the environment: it enhances the greenhouse effect, causes acid rain, decreases the quality of water, and contaminates the groundwater. One liter of used oil can contaminate about 7 Ml of ground waters. The pollution of water with petroleum products reduces the amount of dissolved oxygen and causes many marine species to die [4]. The contamination of soil with hydrocarbons makes its further use for agricultural purposes impossible.

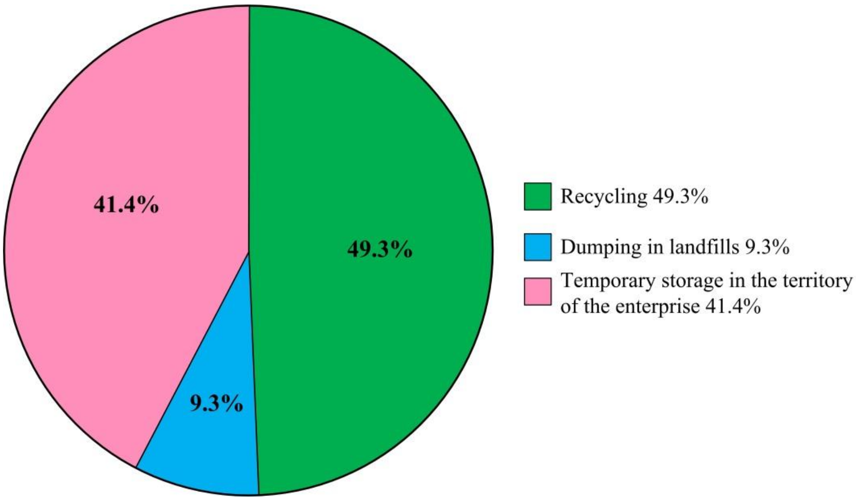

Figure 1. Industrial waste recovery structure in the Russian Federation [3].

The volume of MSW (paper, cardboard, plastic, wood, and textiles) production in the Russian Federation in 2016 made up 52.4 Mt. About 3.9 Mt of MSW, or 7.4%, were destined for re-use (Figure 2). About 1.0 Mt of MSW, or 1.9%, were transferred for decontamination and destruction, including by burning it at trash incineration plants. The overwhelming majority of waste (47.5 Mt, or 90.7%) went to waste disposal and landfill sites for burial and temporary storage [3].

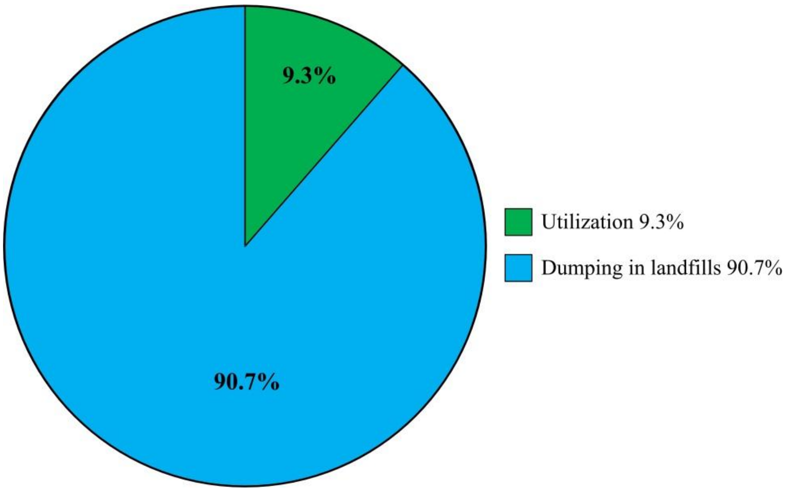

Figure 2. Municipal solid waste (MSW) recovery structure in Russian Federation [3].

The extremely low MSW recovery indicators are explained by the low level of waste management development. There are only 243 MSW recovery complexes, 53 sorting complexes, and 10 trash incineration plants in the whole Russian Federation. The number of specially equipped facilities for waste disposal (MSW disposal sites) in the country is about 1399, which is several times lower than the number of authorized landfill sites (there are 7153 of them). Unauthorized landfill sites number more than 17,500. They pose the biggest environmental threat. In the waste management structure, they are regarded as environmental damage that has already been built up over the last years. Dedicated waste disposal sites, authorized and unauthorized MSW landfill sites take up huge amounts of land with a total area of more than 50,000 ha. Landfill storage of non-recovered waste entails the following negative factors: a wide spread of substances and bacterial flora that are dangerous for people's health, including when they find their way into the air and ground waters; formation of dioxides if ignition occurs; low economic performance indicators taken the environmental risks, the costs of land and waste disposal site maintenance.

Low level of waste management development in the Russian Federation does not conform to the "Basic Principles of National Policy for Environmental Development of the Russian Federation for the period until 2030" [5]. It is a current objective to develop routines that will effect the transition from waste stockpiling towards recovery and re-use. Additionally, minimizing the adverse effects on the environment of the waste already accumulated is a priority.

According to the global experience, discontinuing waste stockpiling and burial in favor of re-use requires the implementation of an intermediate stage in the medium term, namely waste disposal by burning to produce heat and electricity [6]. Such routines will reduce the annual growth rates of industrial and municipal waste, and, in some cases, will allow for partial or complete recovery of the accumulated waste that is unsuitable for re-use. It is an important task to develop routines for using industrial waste and MSW to reduce the load of landfill sites and improve the environmental situation around them. Normally, such problems are solved by simply burning waste [7] or by burning waste with energy generation [8]. However, the low calorific value of MSW (about 10 MJ/kg [9]) versus that of conventional coal fuels (20–30 MJ/kg [10]), as well as a relatively high concentration of harmful gases make complete replacement of coal with combustible waste not economically, environmentally or technically viable.

An alternative approach to solving this problem is to use fine MSW as a composite liquid fuel component consisting of coal processing waste (or a mixture of low-quality brown or bituminous coals with water) and a used combustible liquid (transformer, turbine, engine oils, etc.). Based on the assessments in [11], it is possible to predict that the introduction of 10–20% of typical municipal solid waste into composite fuels will decrease the territories of new landfill sites built for MSW burial by 25%. Besides it will provide for more economical use of non-renewable hydrocarbon fuels that nowadays are directly burned to produce heat and electricity.

Based on the above, the purpose of this research is to experimentally study the patterns and characteristics of composite fuel ignition and combustion, as well as to analyze the prospects of joint implementation of industrial and municipal waste recovery strategy with power generation at local thermal power plants by several neighboring regions of the Russian Federation.

The relevance of the present study is explained by the following: expanding the scope of raw materials in thermal power engineering by using relatively cheap composite fuels from waste rather than high-grade coals saves solid fossil fuels and financial means for their acquisition. As a rule, a limited amount of accumulated or annually produced combustible waste in a separate region does not allow to implement a strategy of efficient waste recovery with energy production on an industrial scale. The authors of the manuscript provide an example of several neighboring regions of the Russian Federation with different levels of social development and different industrial structures to validate the prospects of combined implementation of the strategy for efficient recovery of industrial and municipal waste with energy production at local thermal power plants.

The novelty of the experimental investigation and theoretical analysis consists in the prospect of practical application of the proposed waste management strategy. The latter would be a temporary strategy while transition is being made from waste burial to re-use or recycling. During the 15–25 years of transition, the waste management strategy will reduce the amount of waste to be buried, on the one hand, and eliminate interim steps involving the construction of costly incineration plants which will be in demand for a relatively short period of time, on the other hand.

2. Experimental Investigation

2.1. Materials Preparation

The research was performed on five fuel compositions based on filter cakes of coking coal (filter cake). Filter cake was produced in the Severnaya coal washing plant that is situated in Kemerovo region of the Russian Federation. Combustible waste is a by-product of coal processing—preparation for long hauls to the consumer. The initial coal is washed with water to remove fine fractions (5–15% of the initial amount of coal). This reduces the level of environmental contamination with coal dust during transportation by trains and sea ship; it also improves fire safety of the coal dust. After the coal has been washed, the liquid containing fine particles is left in tanks. These particles (up to 80 µm in size) settle on the bottom. The upper layer of water is pumped for re-use. The liquid residue is passed through press filters. The moist residue is the filter cake with water content about 40%. At the locations of the coal washing plants, filter cakes are stockpiled on open sites. Large areas are contaminated not only by stockpiled filter cake, but also by a fine coal dust that pollutes the surrounding lands due to the wind.

Previous research findings of composite fuel ignition and combustion [12] processes (filter cakes + used oil) testify to the fact that filter cakes can be used as the main combustible component when preparing composite fuels based on industrial waste and MSW. Taking into account the high level of coal mining (about 7.5 Mt) and consumption in the thermal power engineering (about 40% of the total power generation), and consequently, rather large production volumes of filter cakes from coal processing, it can be concluded that filter cakes are a promising component for composite fuels [13].

Wet filter cakes (with a coal mass fraction of about 60%) were used in this study as the main component of our composite fuels. Five different compositions are used in experiments: No. 1—filter cake 100%; No. 2—filter cake 95% + used engine oil 5%; No. 3—filter cake 85% + wood 10% + used engine oil 5%; No. 4—filter cake 85% + rubber 10% + used engine oil 5%; No. 5—filter cake 85% + plastic 10% + used engine oil 5%. The mass fractions are listed here. The particle size of typical municipal solid waste is comparable to that of coal particles (about 100 µm). The main characteristics of the fuel components are listed in Tables 1–3. The characteristics of the filter cake are presented for dry samples. The filter cake has been dried at about 105 °C until the moisture has fully evaporated.

Fuel droplets were generated by an electronic dispenser (limit dosage volumes were 1 µL and 10 µL, pitch variation was 0.1 µL). The fuel droplet size (diameter) was about 2 mm (the volume was about 4.2 µL, the mass about 3.9 mg).

Table 1. Properties of fuel components. Proximate analysis.

Component	W^a, %	A^d, %	V^{daf}, %	$Q^a_{s,V}$, MJ/kg	References
Filter cake	-	26.5	23.1	24.83	[14]
Wood	20.0	2.0	83.1	16.45	[15]
Rubber	2.0	1.8	67.4	33.50	[9]
Plastic	2.0	0.2	99.5	22.00	[9]
Motor oil	0.3	0.8	100.0	44.02	[15]

Table 2. Properties of fuel components [9,14,15]. Ultimate analysis.

Component	C^{daf}, %	H^{daf}, %	N^{daf}, %	S^{daf}, %	O^{daf}, %	References
Filter cake	87.2	5.1	2.1	1.1	4.5	[14]
Wood	50.3	6.0	0.2	0.1	43.4	[15]
Rubber	97.9	1.2	0.3	0.6	-	[9]
Plastic	66.7	7.9	-	-	25.4	[9]

Table 3. Flash temperature and ignition temperature of fuel components.

Component	Flash Temperature, °C	Ignition Temperature, °C
Filter cake	-	450
Wood	230	340
Rubber	-	350
Plastic	306	415
Motor oil	132	218

2.2. Experimental Setup and Procedure

Ignition and combustion processes of composite liquid fuel droplets of different compositions have been researched using the experimental setup shown in Figure 3. The setup enables one to simulate the conditions of fuel droplet heating that are identical to heating conditions in a boiler furnace. The setup is based on a rotary muffle furnace R 50/250/13 (Nabertherm GmbH, Lilienthal, Germany). The inner diameter of the ceramic tube is 0.04 m and the tube length is 0.45 m; the temperature variation range is 20–1200 °C; the temperature is controlled by the signal of an integrated type S thermocouple. The experiments were conducted after the furnace was heated up to the given temperature. Fuel droplets generated by the dispenser were placed on the holder and introduced to the furnace by the robotic arm through one of the side apertures of the ceramic tube along the tube symmetry axis. The linear velocity of the robotic arm movements did not exceed 0.5 m/s to prevent the droplet deformation and sliding off the holder. A high-speed video camera was fixed on the robotic arm and moved with the holder with a fuel droplet on it. Such scheme made it possible to record all the physical and chemical processes occurring from the moment a fuel droplet was introduced into the furnace up to its burnout. The droplet remained in the video camera focus throughout the whole period of process recording.

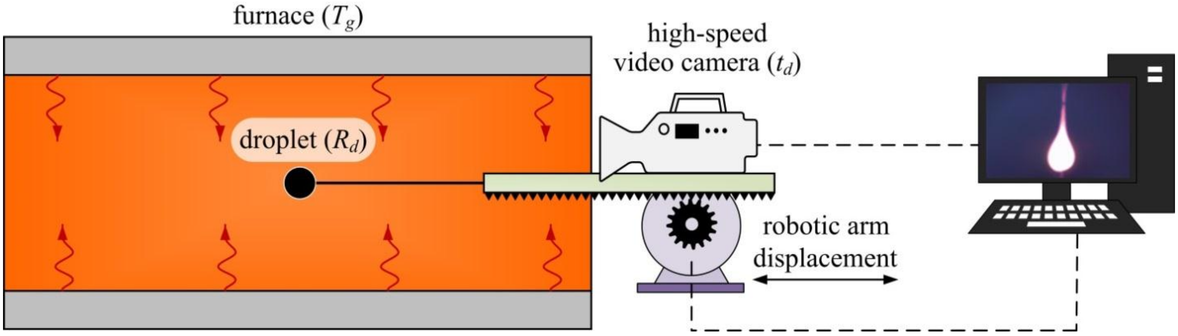

Figure 3. Scheme of experimental setup.

The following parameters were controlled when a series of five experiments under identical initial conditions were conducted: the temperature (T_g) of the heated air in the furnace, the initial diameter (D_d) of the droplet, and ignition delay times (t_d) of the fuel. The air temperature in the furnace was controlled by the readings of a built-in thermocouple. The processes taking place during the fuel droplet heating were recorded by a Phantom v411 high-speed color camera (Vision Research Inc, Wayne, NJ, USA). Its main specifications are as follows: 12 Gb memory; filming rate 4200 frames/s at maximum resolution 1280 × 800 pixels; pixel size 20 μm; 12 bit depth; minimal exposure 1 μs. The Tema Automotive Video software (Image Systems AB, Linköping, Sweden) was used to analyze the video recordings of the experiments. The software and high-speed video recording hardware system made it possible to record fuel droplet characteristics and conduct an analysis of consistent patterns in their combustion. The diameter of the droplet was recorded before it was placed into the muffle furnace. Using the Tema Automotive algorithms, four droplet diameters were automatically measured in four sections. The obtained values were arithmetically averaged and the droplet diameter D_d was then calculated. The systematic error of D_d determination did not exceed 4%. The ignition delay time (t_d) was also calculated automatically as a time interval between two events [16]: the introduction of the fuel droplet into the furnace (heating initiation) and the emergence of luminance around the droplet that corresponds to the moment of gas-phase ignition [17]. The values of t_d were determined by the Threshold algorithm of the Tema Automotive software. The systematic error of t_d did not exceed 3%. Random errors did not exceed 10% for sets of five experiments under identical conditions.

2.3. Experimental Results and Discussion

The results of the experimental research (Figure 4) allow us to conclude that the fuel compositions under study, based on coal processing waste and typical MSW, are ignited consistently when heated in an oxidizing environment (air). The fuel droplet combustion processes continues until the liquid and solid combustible components burn out. It can be concluded that composite fuels based on coal processing waste and typical MSW can be used in thermal power engineering instead of conventional coals.

It has been established that the ignition and combustion patterns of all the composite fuel compositions (Figure 4) with 5–15% of a combustible liquid and MSW are similar to those of the initial filter cakes (composition No. 1). The experimental result can be explained by the dominant influence of this component on the physical and chemical processes during the fuel droplet heating. A possibility of varying the component composition and concentration of separate components of composite fuels in wide ranges creates favorable conditions of using such fuels with predictable characteristics in real life. Wet filter cakes in their initial state and used oils (transformer, turbine, engine, etc.), or filter cakes with a relatively low moisture content (moisture evaporates in the process of storing them at disposal sites) with industrial or municipal sewage water containing combustible liquids can be used to prepare composite fuels. According to the results (Figure 4), adding about 10% of typical MSW to composite fuels does not change the consistent patterns and characteristics of ignition and combustion of the latter. This result may serve as a foundation for a strategy of MSW industrial recovery with energy generation.

At relatively high air temperatures (above 700 °C) in the muffle furnace, the conditions of heating, ignition and combustion of the fuel droplet introduced into it correspond to those of the same processes occurring in the boiler furnace. The following main stages of interdependent physical and chemical processes have been highlighted: inert heating; moisture evaporation from the subsurface layer; thermal decomposition of solid combustible components (coal and MSW); combustible gases mixing with the oxidizer; gaseous mixture ignition and burnout; heating of the solid combustible residue; the heterogeneous ignition and combustion of the solid residue. The video frames of the processes under study show (Figure 4) that at the moment of the gas-phase ignition t_d, the combustible gas mixture forming around the droplet is spherical. The size of this mixture equals 2–3 sizes of the fuel droplet. The more components with a high content of volatiles in the fuel composition and the lower the ambient temperature, the larger the size of the forming gas zone (up until the ignition) around the fuel droplet. This result is explained by the following. At the ignition moment (less than 5 s after heating), the fuel droplet is heated unevenly in conditions of relatively high ambient temperatures (800 °C and above). The evaporation and thermal decomposition processes are not complete. They only take place in the near-surface layer of the fuel droplet. The gas-phase ignition of vapors occurs in the immediate vicinity of the droplet. At relatively low ambient temperatures

(600 °C), the ignition delay time t_d is substantially higher (more than 12 s) than it is at 800 °C and above. During such a long time period, the droplet is warmed up evenly. In such conditions, the intensity of fuel evaporation and thermal decomposition is higher than it is at the temperatures above 800 °C. As a result, the concentration of vapors and the size of the gas zone in the vicinity of the droplet are bigger at the moment of ignition.

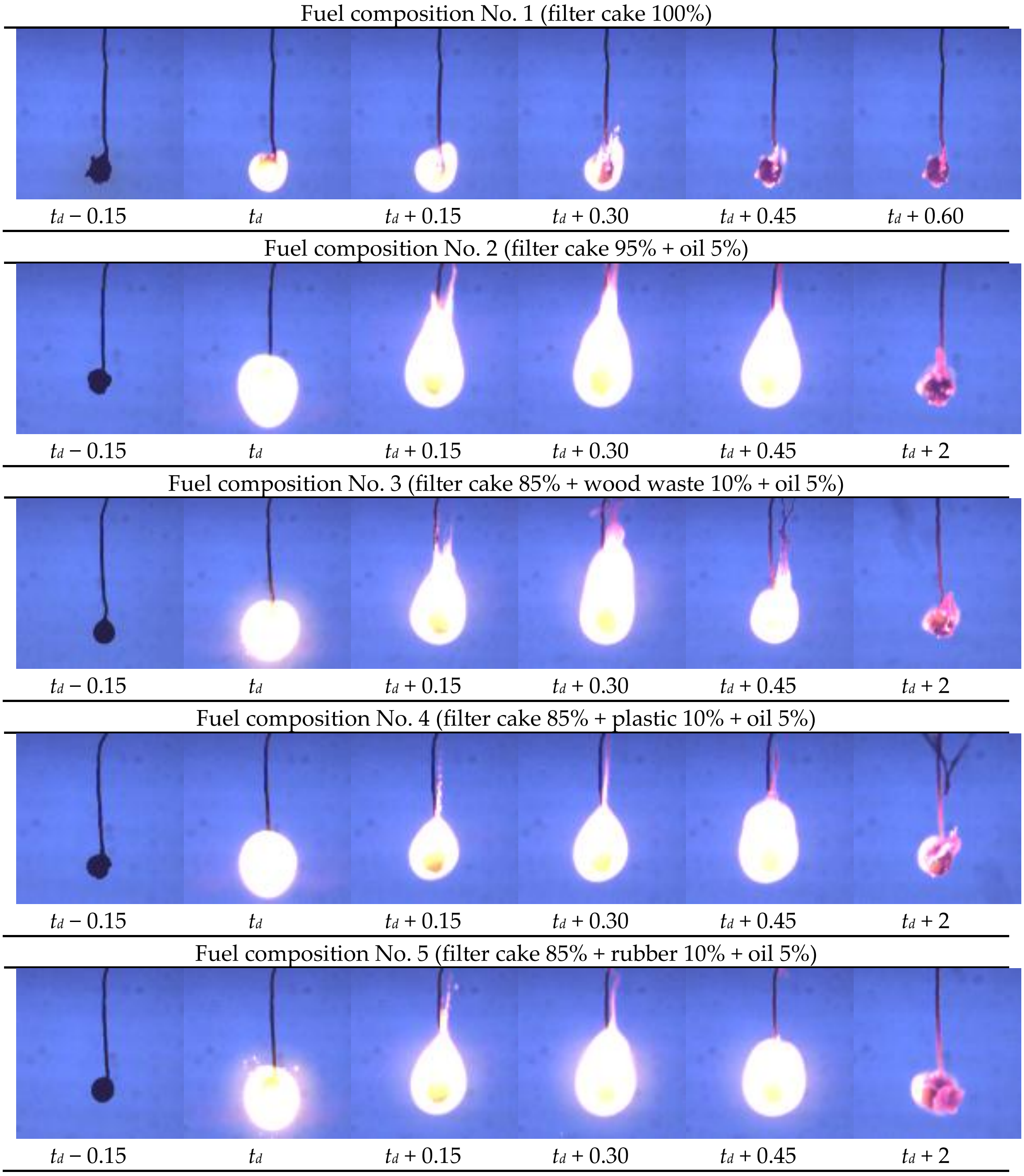

Figure 4. Ignition and combustion of composite liquid fuel droplet at T_g = 800 °C (t_d, s).

After the ignition, the gas-phase combustion process of the volatiles takes place predominantly above the droplet (Figure 4) where a stoichiometric ratio occurs between the components (oxidizer and fuel) of the gaseous mixtures. The intensity of the flame in the frame with $t = (t_d + 0.30)$ s (Figure 4) is lower in the lower regions of the droplet. The intensity increases when going vertically (upwards from the droplet bottom). It means that a rich premixed flame zone is present in this region, where the oxidizer concentrations are relatively higher than the fuel concentrations [18]. The intensity of evaporation and thermal decomposition of the composite fuel components is quite low. This causes the flame to appear nearer to the droplet surface. As a result, the solid combustible residue is heated by the energy released from the process of the gaseous mixture burnout, and then it ignites. The combustion front is spread inside the droplet from its surface to the center. For the municipal waste investigated in this research, the share of a non-combustible solid residue is much smaller than that for the filter cake (Table 1). Adding MSW into the fuel composition causes not only a pronounced gas-phase combustion of volatiles around the droplet to take place, but also reduces the ash residue after the burnout of combustible components.

Figure 5 contains a crosshatched region that illustrates the range of changing the main process characteristics (t_d) under guaranteed ignition conditions of different composite fuel compositions when the air temperature T_g was varied from 600 to 1000 °C. The upper limit of the region (Figure 5) is a curve characterizing ignition delay times of the initial filter cake (without adding MSW and combustible liquid) vs. temperature. The lower limit of the region (Figure 5) is a curve $t_d = f(T_g)$ obtained for the fuel composition based on filter cakes, plastic, and used oil. The ignition delay times of other compositions lie within the boundaries of the crosshatched region (Figure 5). The results from Figure 5 make it possible to conclude that the air temperature 600 °C is the minimum necessary for the ignition process of composite fuels based on coal processing waste, MSW, and a combustible liquid to initiate. The maximum difference in t_d for compositions with different components makes up less than 20% at the air temperatures 600–1000 °C. It was also established that at the air temperature above 1000 °C, the intensity of processes occurring during the induction period is so high that the heat and mass transfer in the droplet and around it has a less significant impact on the ignition characteristics than at T_g = 600–1000 °C. When T_g > 1000 °C, the ignition delay times for the identical fuel droplet with the same composition are only marginally different. For example, at T_g = 1100 °C and T_g = 1200 °C the difference in t_d is less than 5%. For a rapid evaluation of mean ignition delay time values of composite fuels (filter cakes 85% + MSW 10% + oil 5%), an approximate equation can be used:

$$t_d \approx 203.1 \exp\left(-0.0044 T_g\right) \text{ at } 600 \leq T_g \leq 1000\ ^\circ\text{C}.$$

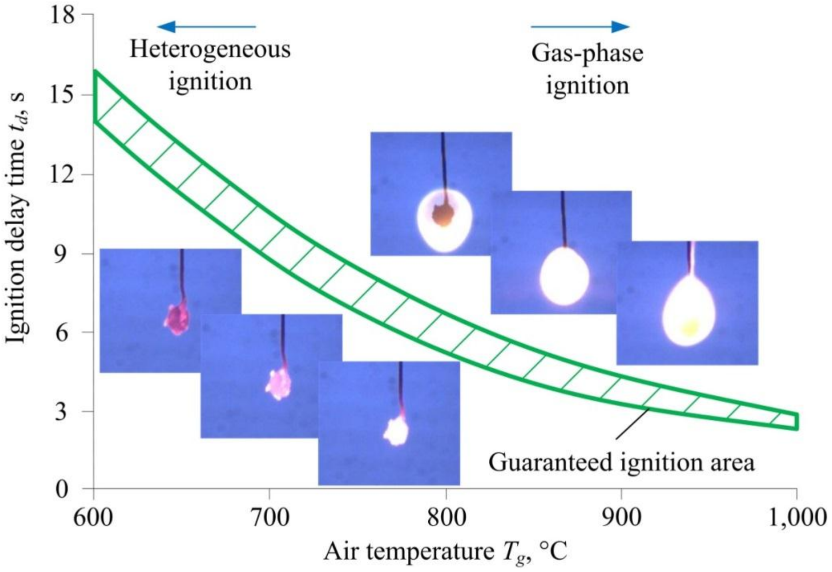

Figure 5. Crosshatched area shows ignition delay times of droplets sized 2 mm of different compositions of composite fuels based on industrial and municipal waste at various air temperatures.

The analysis of the high-speed video recordings of composite fuel ignition and combustion processes under the conditions of low ($T_g \approx$ 600–700 °C), moderate ($T_g \approx$ 700–800 °C) and high (T_g > 800 °C) intensity of the droplet heating made to possible to determine consistent patterns of the occurring physical and chemical processes, which can be used in the development of a relevant mathematical model. At relatively low temperatures, the duration of the induction period is rather long (14–16 s) (Figure 5). Under such conditions, the intensity of the occurring thermal decomposition of combustible components is not high. Due to the heat and mass transfer processes in the vicinity of the fuel droplet, the concentration of combustible gases is not high enough for the combustion process to initiate. The heterogeneous ignition and subsequent combustion with a relatively low intensity is typical of the temperatures $T_g \approx 600$–$700\ ^\circ$C. In the range of high temperatures (above 700 °C), the intensities of heating the subsurface droplet layer, thermal decomposition of combustible components and formation of the gas mixture are high (Figure 5). Figure 4 illustrates the above regularity of physical and chemical processes under such conditions.

The research findings (Figures 4 and 5) lead to an important practical conclusion that it is possible to efficiently recover typical MSW at thermal power engineering facilities. Besides, adding MSW into the main fuel will allow to reduce fuel consumption without worsening the energy performance characteristics of the process (see combustion heat values in Table 1).

3. Prospects for Utilization of Industrial and Municipal Waste from Several Regions by Burning with Energy Generation

In most countries with a developed primary economic sector (primarily due to fossil fuel mining), regions where fossil fuels are extracted tend to be surrounded by other regions with a high level of industrial and social development (Figure 6). This neighborhood creates favorable conditions for increasing the volumes of fossil fuel extraction, on the one hand, and for the development of industrial enterprises and population growth, on the other hand. In such conditions, regions with a developed primary sector of the economy, e.g., due to coal mining and exporting, have to deal with a major problem of reducing the negative environmental impact from coal washing plants storing filter cakes at open-air disposal sites. The main problem of regions with a high level of industrial and social development is recycling and recovery of MSW whose annual production volume is comparable to that of industrial waste of large coal mining and coal processing enterprises, which reaches millions of tons a year.

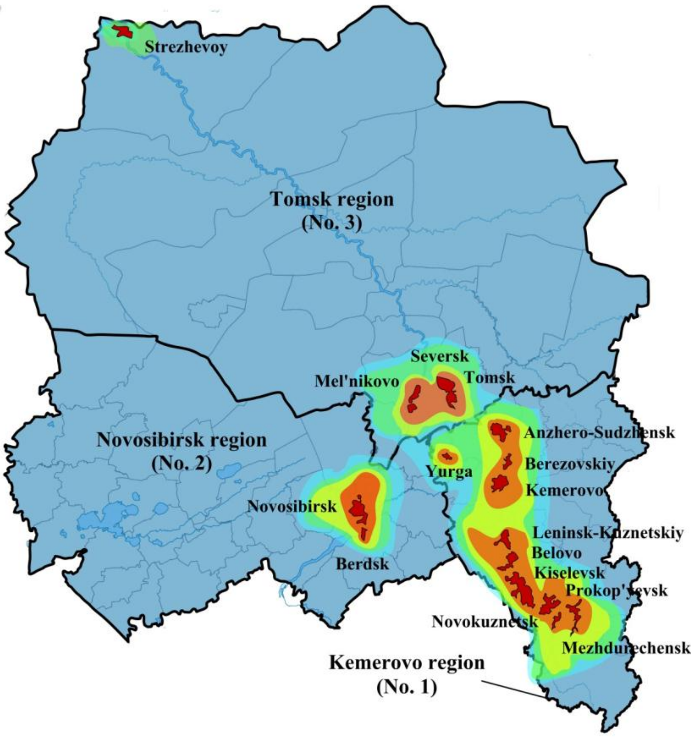

Figure 6. Location of industrial waste and MSW sources [5].

It appears promising for the neighboring regions to solve these problems in a comprehensive way by implementing a strategy of combined recovery of industrial and municipal waste by burning it as part of composite fuels at local thermal power plants. It will reduce the negative impact of waste on the environment, on the one hand, and diminish the consumption volume of high-grade coals for heat and electricity generation, on the other hand. In this research, the main elements of the proposed strategy have been elaborated using three neighboring regions of the Russian Federation located in Western Siberia as an example: Kemerovo region (No. 1), Novosibirsk region (No. 2), and Tomsk region (No. 3). The obtained results will serve as a foundation for developing similar waste management strategies in other regions of the world, considering their peculiar features.

It is believed that in practice, the new waste management strategy will be implemented in a rather short period of time (15–25 years). This strategy is likely to be in great demand among countries with no MSW recycling but burial at disposal sites, so the proposed waste management strategy will be a temporary solution in the transition from waste burial to re-use or recycling. During this period, it is essential to minimize the volumes of non-recycled waste disposal. Additionally, organizing complicated technologies of MSW re-use or recycling requires time to streamline the processes at each stage—from separate collection of waste by citizens to re-use as raw materials by industrial enterprises. Therefore, within this time, the proposed waste management strategy will reduce the amount of waste to be buried, on the one hand, and eliminate interim steps involving the construction of costly incineration plants which will be in demand for a relatively short period of time, on the other hand.

3.1. General Information

In the Kemerovo region (No. 1), 2801 Mt of waste are annually produced, MSW making up 0.9 Mt of it. Overall in the region, there are 173,159 MSW sources, 139 fossil fuel extraction sources, 538 manufacturing waste sources, 1517 sources of production and non-production waste (materials and goods that lost their consumer properties), 497 sources of waste related to power, gas, and vapor supply, 294 sources of water supply and sewage water disposal waste, 176 sources of construction and repair waste, 72 sources of agricultural, forestry, fish-farming, and fishing waste, as well as 1073 sources of other waste. The MSW breakdown is presented in Figure 7.

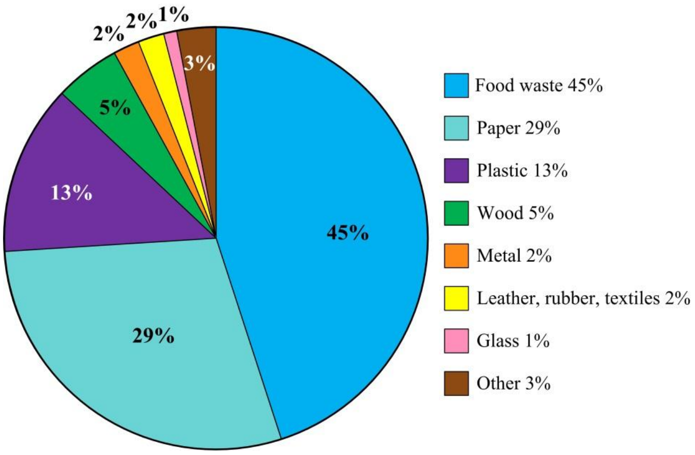

Figure 7. MSW structure of the Kemerovo region (No. 1).

About 98% of all the MSW are stockpiled and buried at disposal sites, and just about 2% are recovered. The Kemerovo region is characterized by an uneven distribution of its MSW production areas: the population density is about 28 people per 1 km^2, of which 85% are concentrated in urban areas. The total population of the region is about 2.7 million people. In each of the five large cities (Kemerovo, Novokuznetsk, Prokop'yevsk, Belovo, and Mezhdurechensk), there are more than 100,000 citizens. Over 80% of the MSW are produced in large cities.

In Kemerovo region, there are deposits of coal, iron ore, gold, silver, manganese, zinc, lead, copper, etc. On an industrial scale, primarily coal (brown and bituminous) is mined. This coal is not only used for thermal power engineering purposes, but is also exported abroad. Coal mining and coal processing enterprises are the main sources of combustible industrial waste. The greatest amount of waste (filter cakes) is produced where major surface mines are located around the city of Kemerovo (39.0%), as well as in "Mezhdurechenskiy" (12.4%), "Kiselyovskiy" (8.9%), "Berezovskiy" (8.6%), and "Prokopievskiy" (7.5%) surface mines.

In the Novosibirsk region (No. 2), 3.9 Mt of waste, of which 1.3 Mt are MSW, are annually produced. The bulk of MSW (1.2 Mt—92.3%) is produced in the regional center (the city of Novosibirsk) and around it (the city of Berdsk). This is conditioned by the fact that 2.2 million people out of the total 2.8 million population live there. About 78% of the MSW is destined for burial. Only a third of MSW disposal sites comply with the current safety requirement regulations. The volumes of MSW stockpiled at disposal sites is growing every year. Near the regional center (the city of Novosibirsk), the volume of waste stockpiled at disposal sites has grown 2.5 times over the last 15 years, and makes up about 70 Mt. The breakdown of the MSW is presented in Figure 8.

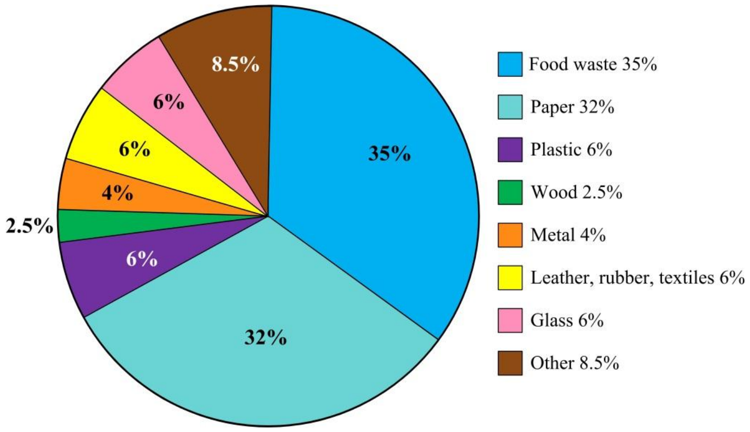

Figure 8. MSW structure of Novosibirsk region (No. 2).

The Novosibirsk region is one of the largest industrial districts of Siberia. The industrial complex is composed of large and medium-sized enterprises producing more than 80% of all the output: agricultural products, foodstuffs, electrical appliances, electronic and optical equipment, metallurgical equipment, metalware and non-metallic products, and construction materials (reinforced concrete). Novosibirsk region annually produces about 2.6 Mt of industrial waste, 43.8% of which is fossil fuel extraction waste, in particular, coal mining waste.

In the Tomsk region (No. 3), 1.3 Mt of waste are annually produced, of which 0.4 Mt are MSW, and 0.9 Mt are industrial waste. The bulk of MSW comes from major cities: Tomsk (0.3 Mt—74.7%) and Seversk (0.03 Mt—7.5%) This is explained by the fact that 0.8 million people out of the total 1.1 million live there. About 98% of MSW are destined to be buried at dedicated waste disposal sites. The MSW breakdown is presented in Figure 9.

The bulk of industrial waste is produced where large industrial facilities are located: in Tomsk (0.3 Mt—26.8%), Seversk (0.3 Mt—24.3%), and near them (0.1 Mt—12.3%). There are about 3500 industrial enterprises in Tomsk region. The structure of industrial production is multisectoral. The main industry branches are: fossil fuel extraction, electric power, non-ferrous mining, chemical, petrochemical, wood, wood working, and food industries, as well as mechanical engineering and metal working. The oil and petrochemical industries, mechanical engineering and metal working take the dominant position (over 60% of the total industrial output). About 0.2 out of 0.9 Mt of the total waste volumes annually produced are recovered at enterprises, 0.2 Mt are delivered to third parties as recyclable materials, and 0.5 Mt are stockpiled at temporary storage sites in the facilities of enterprises or buried at dedicated disposal sites.

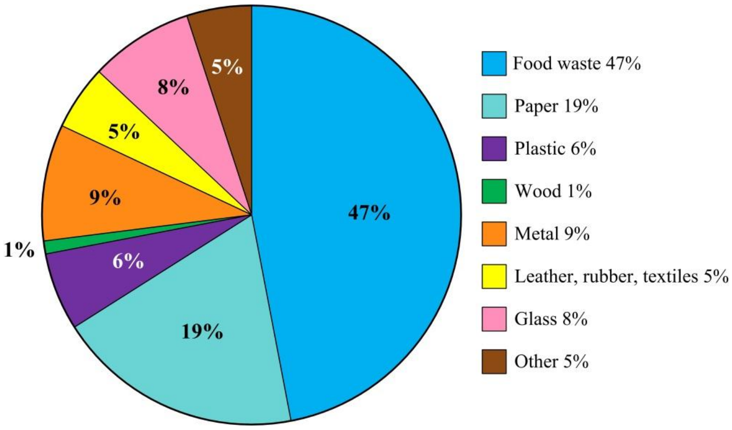

Figure 9. MSW structure of Tomsk region (No. 3).

3.2. *Energy Potential of Industrial Waste and Municipal Solid Waste (MSW)*

Tables 4–6 present the main data used to calculate the energy potential of industrial and municipal solid waste in three neighboring regions (Figure 6) of the Russian Federation.

Table 4. Characteristics of waste by regions [5].

Characteristics	Kemerovo Region (No. 1)	Novosibirsk Region (No. 2)	Tomsk Region (No. 3)
Total volume of waste, Mt/y	2801	3.9	1.3
Industrial waste, Mt/y	2800	2.6	0.9
Structure of industrial waste:			
• fossil fuel extraction waste	99.5%	43.8%	17.2%
• manufacturing industry waste	0.2%	8.1%	32.8%
• waste related to generation and distribution of power, gas, and water	0.1%	24.5%	7.2%
• construction and repair waste	<0.01%	0.1%	1.0%
• agricultural, forestry, fish-farming, and fishing waste	0.04%	16.0%	32.9%
• other waste	0.15%	7.5%	8.9%
Re-use/recovery, Mt/y	1876.0 (67.0%)	0.9 (34.1%)	0.3 (28.0%)
Burial/stockpiling at disposal sites, Mt/y	924.0 (33.0%)	1.7 (65.9%)	0.6 (72.0%)
Municipal solid waste (MSW), Mt/y	0.9	1.3	0.4
The structure of MSW:			
• food waste	45%	35%	47%
• paper	29%	32%	19%
• plastic	13%	6%	6%
• metal	2%	4%	9%
• leather, rubber, textiles	2%	6%	5%
• glass	1%	6%	8%
• wood	5%	2.5%	1%
• other	3%	8.5%	5%
Re-use/recovery, Mt/y	0.02 (1.9%)	0.3 (22%)	0.008 (2.0%)
Burial/stockpiling at disposal sites, Mt/y	0.88 (98.1%)	1.0 (78%)	0.392 (98.0%)

Table 5. Volume of sewage water produced in oil processing (per 1 t of oil) [3].

Type of Plant	Volume of Sewage Water Produced, m³/t of Oil	
	of the First System	of the Second System
Fuel refinery plant	0.23–0.25	0.10–0.20
Lube and fuel refinery plant	0.40–1.50	0.10–0.25
Petrochemical plant	2.00–3.00	1.20–2.00

Table 6. Heat of combustion of typical MSW [9].

Type of Waste	Heat of Combustion, MJ/kg
Food waste	5–10
Paper	15–20
Plastic	20–25
Leather, rubber, textiles	20–35
Wood	15–20
Other	<10

The source data to calculate the energy potential of MSW is as follows:

MSW that has been already accumulated and not recovered as of 2017 (stockpiled at disposal sites) ($G^0{}_{\mathrm{MSW}}$):

- in Kemerovo region—54.0 Mt;
- in Novosibirsk region—70.0 Mt;
- in Tomsk region—21.0 Mt.

The annual production volume of MSW (G_{MSW}):

- in Kemerovo region—0.9 Mt;
- in Novosibirsk region—1.3 Mt;
- in Tomsk region—0.4 Mt.

The share of non-recovered combustible MSW stored at disposal sites (k^{MSW} coefficient) for every region:

- in Kemerovo region—0.5;
- in Novosibirsk region—0.7;
- in Tomsk region—0.6.

The averaged heat of combustion (q^{MSW}) for typical MSW composition is (Table 6):

- in Kemerovo region—14.1 MJ/kg;
- in Novosibirsk region—12.0 MJ/kg;
- in Tomsk region—10.0 MJ/kg.

The energy potential from burning the MSW accumulated by 2017 in every region:

$$Q^0{}_{\mathrm{MSW}} = G^0{}_{\mathrm{MSW}} \times q^{\mathrm{MSW}} \quad (1)$$

- in Kemerovo region $Q^0{}_{\mathrm{MSW}} = 54.0 \times 10^6 \times 10^3 \times 14.1 \times 10^6 = 761$ PJ;
- in Novosibirsk region $Q^0{}_{\mathrm{MSW}} = 70.0 \times 10^6 \times 10^3 \times 12.0 \times 10^6 = 830$ PJ;
- in Tomsk region $Q^0{}_{\mathrm{MSW}} = 21.0 \times 10^6 \times 10^3 \times 10.0 \times 10^6 = 209$ PJ.

The energy potential from burning MSW accumulated within a year:

$$Q^{\text{MSW}} = k^{\text{MSW}} \times G^{\text{MSW}} \times q^{\text{MSW}} \quad (2)$$

- in Kemerovo region $Q^{\text{MSW}} = 0.5 \times 0.9 \times 10^6 \times 10^3 \times 14.1 \times 10^6 = 13$ PJ;
- in Novosibirsk region $Q^{\text{MSW}} = 0.7 \times 1.3 \times 10^6 \times 10^3 \times 12.0 \times 10^6 = 15$ PJ;
- in Tomsk region $Q^{\text{MSW}} = 0.6 \times 0.4 \times 10^6 \times 10^3 \times 10.0 \times 10^6 = 2$ PJ.

3.3. Energy Potential of Coal Processing and Oil Refining

The source data to calculate the energy potential of filter cakes and low rank coals is as follows:

Filter cakes ($G^0{}_{\text{fc}}$) that have been accumulated and not recovered (are stored at disposal sites) by 2017 in every region:

- in Kemerovo region—368.6 Mt;
- in Novosibirsk region—5.8 Mt;
- in Tomsk region, coal is not extracted or processed.

The annual production volume of filter cakes (G_{fc}) makes up 10–15% of the volume of processed coal:

- in Kemerovo region—8.1 Mt;
- in Novosibirsk region—0.4 Mt;
- in Tomsk region, coal is not extracted or processed.

The heat of combustion (q_{fc}) of typical filter cakes (Table 1) is about 24.8 MJ/kg.

The energy potential from burning the filter cakes accumulated by 2017:

$$Q^0{}_{\text{fc}} = G^0{}_{\text{fc}} \times q_{\text{fc}} \quad (3)$$

- in Kemerovo region $Q^0{}_{\text{fc}} = 368.6 \times 10^6 \times 10^3 \times 24.8 \times 10^6 \times 0.6 = 5485$ PJ;
- in Novosibirsk region $Q^0{}_{\text{fc}} = 5.8 \times 10^6 \times 10^3 \times 24.8 \times 10^6 \times 0.6 = 86$ PJ;
- in Tomsk region $Q^0{}_{\text{fc}} = 0$ J.

The energy potential from burning filter cakes accumulated within a year:

$$Q_{\text{fc}} = G_{\text{fc}} \times q_{\text{fc}} \quad (4)$$

- in Kemerovo region $Q_{\text{fc}} = 8.1 \times 10^6 \times 10^3 \times 24.8 \times 10^6 \times 0.6 = 201$ PJ;
- in Novosibirsk region $Q_{\text{fc}} = 0.4 \times 10^6 \times 10^3 \times 24.8 \times 10^6 \times 0.6 = 10$ PJ;
- in Tomsk region $Q_{\text{fc}} = 0$ J.

The source data to calculate the energy potential of liquid combustible waste (used oils). Used oils, combustible oil production and refining waste ($G^0{}_{\text{oil}}$) that have been accumulated and not recovered (are stored at disposal sites) by 2017 in every region:

- in Kemerovo region, there is no liquid combustible waste;
- in Novosibirsk region—97.3 kt;
- in Tomsk region—2219 kt.

The annual production volume of used oils, combustible oil production and refining waste (G_{oil}):

- in Kemerovo region—0.5 kt;
- in Novosibirsk region—0.7 kt;

- in Tomsk region—11.5 kt.

About 40% of used oils are not recovered (l_{oil} coefficient). They can be used to produce composite fuels. The heat of combustion (q_{oil}) of typical combustible liquids is 44.0 MJ/kg. The energy potential from burning the used oils accumulated by 2017:

$$Q^0{}_{oil} = G^0{}_{oil} \times q_{oil} \tag{5}$$

- in Kemerovo region $Q^0{}_{oil} = 0$ J;
- in Novosibirsk region $Q^0{}_{oil} = 97.3 \times 10^3 \times 10^3 \times 44.0 \times 10^6 = 4$ PJ;
- in Tomsk region $Q^0{}_{oil} = 2219.4 \times 10^3 \times 10^3 \times 44.0 \times 10^6 = 98$ PJ.

The energy potential from burning used oils accumulated within a year:

$$Q_{oil} = l_{oil} \times G_{oil} \times q_{oil} \tag{6}$$

- in Kemerovo region $Q_{oil} = 0.4 \times 0.5 \times 10^3 \times 10^3 \times 44.0 \times 10^6 = 0.009$ PJ;
- in Novosibirsk region $Q_{oil} = 0.4 \times 0.7 \times 10^3 \times 10^3 \times 44.0 \times 10^6 = 0.012$ PJ;
- in Tomsk region $Q_{oil} = 0.4 \times 11.5 \times 10^3 \times 10^3 \times 44.0 \times 10^6 = 2$ PJ.

The results of the conducted study are presented in Table 7. It can be concluded that industrial waste and MSW already accumulated and annually produced have a rather high level of energy potential. In the medium term, such waste can be used to satisfy the needs for energy resources when local coal-fired thermal power plants generate energy.

Table 7. Energy potential of each region due to accumulated and annually produced waste.

Energy Resources	Accumulated in Total		Annual Growth	
	G^0, Mt	Q^0, PJ	G, Mt	Q, PJ
Kemerovo region (No. 1)				
Filter cakes	368.8	5485	8.1	121
MSW	54.0	761	0.9	13
Petroleum products	-	-	0.0005	0.009
Novosibirsk region (No. 2)				
Filter cakes	5.8	86	0.4	6
MSW	70.0	830	1.3	15
Petroleum products	0.0973	4	0.0007	0.012
Tomsk region (No. 3)				
Filter cakes	-	-	-	-
MSW	21	209	0.4	2
Petroleum products	2.2	98	0.0115	2
Overall data for three regions				
Filter cakes	374.6	5571	8.5	127
MSW	145.0	1800	2.6	30
Petroleum products	2.3	102	0.0127	2

3.4. Need for Energy Resources of Coal-Fired Thermal Power Engineering

The regions under study (Figure 6) receive their auxiliary heat and electricity supply primarily from local thermal power plants. In the Kemerovo and Novosibirsk regions, bituminous coals extracted at local deposits are the main fuel, whereas natural gas is a backup fuel. In the Tomsk region, the natural gas extracted locally is the main energy resource. Despite this, all the boilers were initially designed and constructed to burn coals. Their modernization and conversion to natural gas was performed after the commercial extraction of the latter was started. The main specifications of thermal power plants are presented in Table 8.

Combined thermal and electric power generation in Kemerovo region is realized at three plants. Smaller boiler plants (about 100 of them), whose total installed heat power is 904 Gcal/h, provide heat mainly to housing and utilities sector, as well as smaller industrial enterprises. There are four main sources of heat and electricity supply in Novosibirsk region. The total installed capacity of boiler plants (over 200 of them) is 3733 Gcal/h. About 93% of this power is generated by boiler plants using natural gas, the rest is generated by coal-fired boiler plants and those using fuel oil. The main sources of heat and electricity supply in Tomsk are three thermal power plants. The total installed capacity of boiler plants (52 of them) is 762 Gcal/h. About 81% of this power is generated by boiler plants using natural gas, the rest is generated by coal-fired boiler plants and those using fuel oil. The main characteristics of coals used as fuel at thermal power plants are presented in Table 9. These are primarily bituminous coals of Kuznetsk and Kansk-Achinsk Basins.

The simultaneous analysis of data from Tables 8 and 9 makes it possible to calculate the amount of coal used by thermal power plants and boiler plants of the three regions to produce heat and electricity. The annual consumption of high-grade coal is about 10,216 kt (Kemerovo region—2664 kt, Novosibirsk region—7149 kt, and Tomsk region—403 kt). The combustion of this amount of coal releases about 217 PJ of heat. This energy is converted into electricity and heat with due consideration of the 70% efficiency of thermal power plants. In the conversion process, the low efficiency of thermal power plants causes irrecoverable losses of a rather large amount of energy released during high-grade coal combustion. A high-grade fuel is used inefficiently. Replacing coal with a composite fuel from coal processing waste (or from low-quality coal), MSW, used oils (or combustible oil production and oil refining waste) will reduce the consumption of high-grade non-renewable fossil fuels.

Table 8. Specifications of thermal power plants [5].

Thermal Power Plant (TPP)	Installed Capacity	Installed Heat Power	Electric Power Generation	Thermal Power Generation	Specific Consumption of Fuel Equivalent per Electric Power Supply	Specific Consumption of Fuel Equivalent per Thermal Power Supply	Fuel Balance			Produced Thermal Power from Burning Coals in Boiler Furnace
							Coal	Gas	Fuel Oil	
	MW	Gcal/h	GW·h	Tcal	g of Fuel Equivalent/kW·h	kg of Fuel Equivalent/Gcal	%	%	%	PJ
Kemerovo region (No. 1)										
TPP 1	485	1540	2053	2524	362	152	76.8	22.8	<0.1	25
TPP 2	80	749	175	725	383	168	91.3	8.7	0	5
TPP 3	565	1449	1946	2911	370	160	99.4	0.5	<0.1	35
Novosibirsk region (No. 2)										
TPP 1	345	920	1122	1899	328.5	146.8	91.1	8.8	0.1	17
TPP 2	511.5	1115	2246	2390	293.5	143.6	99.7	0	0.3	29
TPP 3	384	1120	1363	2251	314.8	143.8	80.9	19.1	0	18
TPP 4	1200	2730	7065	4652	292.9	138	99.5	0.1	0.4	79
Tomsk region (No. 3)										
TPP 1	14.7	795	3.3	651	326	138	0	99.9	<0.1	0
TPP 2	140	780	746	1694	268.5	131	0	99.9	<0.1	0
TPP 3	331	815	1104	2154	249	159.6	47.6	52.4	0	9
Overall data for three regions										
-	4056	12,013	17,823	21,851	-	-	-	-	-	217

Table 9. Characteristics of coals used for power generation [5].

Coal-Fired TPP	Coal	$Q^a{}_{s,V}$, MJ/kg	W^a, %	A^d, %	V^{daf}, %
Kemerovo region (No. 1)					
TPP 1	Low-caking coal	21.8	13.7	17.2	27
TPP 2	Long-flame coal	21.8	14.7	15.4	42.3
TPP 3	Flame coal	21.4	14.1	13.1	41.2
Boiler plants	Flame coal	21.4	14.1	13.1	41.2
Novosibirsk region (No. 2)					
TPP 1	Low-caking and nonbaking coals	24.7	8.3	16.9	23.9
TPP 2	Low-caking and nonbaking coals	22.1	17.5	15.5	19.1
	Brown coal	14.8	35.7	7.6	46.4
TPP 3	Low-caking and nonbaking coals	25	9	15.7	19
TPP 4	Gas coal and flame coal	21.6	14.7	13.1	41.4
Boiler plants	Low-caking and nonbaking coals	24.9	8.3	16.9	23.9
	Brown coal	14.8	35.7	7.6	46.4
	Low-caking and nonbaking coals	21.8	14.7	13.1	41.4
Tomsk region (No. 3)					
TPP 3	Flame coal	21.4	14.1	13.1	41.2
Boiler plants	Flame coal	21.2	13.9	14.5	44.7
	Long-flame coal	21.8	12	15.9	48

3.5. Strategy of Combined Recovery of Industrial Waste and MSW with Power Generation

Tables 7 and 8 present data on the energy potential of industrial waste and MSW, as well as on the amount of thermal energy produced from burning coal in boiler furnaces of thermal power plants. The comparison of respective characteristics enables to draw a conclusion about the prospects of using composite fuels from coal processing waste, low rank coals, MSW, used oils, combustible oil production and oil refining waste, whose annual production and stocks will, in the medium term (20–30 years), satisfy the needs of coal-fired thermal power engineering of the three regions (Figure 6) for energy resources for 100%.

The strategy of combined recovery of industrial and municipal waste by burning it as part of composite fuels implies the following. All the energy (about 217 PJ) (Table 8) generated by coal-fired thermal power plants will be produced by burning a composite fuel. A typical composition of such fuel is 85% of filter cakes (or a mixture of a low rank coal with water) + 10% of MSW + 5% of used oil. The replacement of coal by an amount of a composite fuel with the equivalent energy output will require in the first year (Table 10): 11.13 Mt of filter cakes; 1.31 Mt of MSW; and 0.65 Mt of used oil. The global forecast for the growth of energy consumption presumes that the amount of energy produced from fuel combustion and necessary for heat and electricity generation will rise by 1% every year (Table 10). The consumption of components used to prepare composite fuels will rise accordingly. According to data in Table 10, a combustible liquid is, in the medium term, a limiting component for the preparation of such composite fuel. After the first four years of implementing the proposed energy program, all the accumulated used oil or liquid combustible waste of oil production and oil refining would be completely recovered, whereas its annual production would not cover the necessary requirements for fuel preparation. Starting with the fifth year, composite fuels should include 85% of filter cakes and 15% of MSW. The annual need for components of such fuel will be at least 11.5 Mt of filter cakes and at least 2.0 Mt of MSW. Table 10 presents by year the composition of the fuel and consumption of each of its components in the implementation of the proposed strategy of waste recovery in the conditions of annual energy consumption growth by 1% vs. the previous year.

Table 10. Component consumption for composite fuel preparation.

Year	Energy from Fuel Combustion, PJ	Coal Consumption, Mt	Composite Fuel Consumption (by Component)			
			Filter Cakes, Mt	MSW, Mt	Oil, Mt	Total, Mt
1	217.0	10.22	11.13	1.31	0.65	13.10
2	219.2	10.32	11.24	1.32	0.66	13.23
3	221.4	10.42	11.36	1.34	0.67	13.36
4	223.6	10.53	11.47	1.35	0.67	13.49
5	225.8	10.63	11.58	2.04	-	13.63
6	228.1	10.74	11.70	2.06	-	13.77
7	230.3	10.84	11.81	2.08	-	13.90
8	232.7	10.96	11.94	2.11	-	14.04
9	235.0	11.06	12.05	2.13	-	14.18
10	237.3	11.17	12.17	2.15	-	14.32
11	239.7	11.29	12.30	2.17	-	14.47
12	242.1	11.40	12.42	2.19	-	14.61
13	244.5	11.51	12.54	2.21	-	14.76
14	247.0	11.63	12.67	2.24	-	14.91
15	249.4	11.74	12.79	2.26	-	15.05
16	251.9	11.86	12.92	2.28	-	15.20
17	254.4	11.98	13.05	2.30	-	15.35
18	257.0	12.10	13.18	2.33	-	15.51
19	259.6	12.22	13.32	2.35	-	15.67
20	262.2	12.34	13.45	2.37	-	15.82
21	264.9	12.47	13.59	2.40	-	15.99
22	267.4	12.59	13.72	2.42	-	16.14
23	270.1	12.72	13.86	2.45	-	16.30
24	272.8	12.84	13.99	2.47	-	16.46
25	275.5	12.97	14.13	2.49	-	16.63
Total:	6129	288.55	314.39	52.82	2.66	369.87

The 25-year implementation of the energy program will ensure the recovery (Table 10) of 314.39 Mt of filter cakes, 52.82 Mt of MSW, and 2.66 Mt of used oil. According to data in Table 7, the proposed measures will completely resolve the issue of recovering the used oils, liquid combustible oil production and oil refining waste, accumulated by 2017, and annually produced coal processing waste, as well as reduce the amount of filter cakes accumulated by 2017 by 84%. Moreover, adding MSW to composite fuels will eliminate the problem of its disposal until the transition has been effected to a new system of waste management with a high share of MSW recovery and re-use, and reduce the volumes of MSW that have been accumulated by 2017 at landfill sites by 36%.

The proposed strategy of combined recovery of industrial and municipal waste by burning it as part of composite fuels has several main positive effects:

(1) Saving on high-grade solid fossil fuels (more than 280 Mt over 25 years) due to reducing their consumption by thermal power engineering through the replacement by composite fuels in the amount equivalent by energy performance indicators (about 315 Mt).
(2) Reducing environmental pollution due to solid waste disposal as part of an environmentally friendly electricity and heat production technology.
(3) Reducing the intensity of landfill site area growth due to scheduled disposal of municipal solid waste.
(4) Efficient investment of financial means saved by reducing energy resource acquisition costs into the development of cutting-edge technologies in commercial thermal power engineering and modernization of thermal power plants.

Experimental research findings [19] enable one to conclude that the main environmental characteristics (CO, CO_2, NO_x, SO_x, and micron-sized ash fraction) of flue gases when burning composite fuels prepared from low rank coals and coal processing waste, water and a combustible liquid are not inferior to those of flue gases from coal dust combustion using the conventional technology of coal-fired thermal power plants. A possibility to vary raw materials for composite fuels in a wide range enables to develop fuel compositions with predictable energy, economy and environmental performance characteristics.

4. Conclusions

(1) The theoretical analysis showed that implementing the strategy of combined recovery of industrial and municipal waste by burning it as part of composite fuels at local thermal power plants is a promising approach for neighboring regions to deal with the waste management issue. One of the regions is characterized by a high level of solid and liquid fossil fuel extraction. In the neighboring regions, fossil fuel mining is underdeveloped, whereas the level of social advancement and industrial output is high. The energy potential of industrial waste and MSW determines the prospects of its recovery by means of burning it as part of composite fuels. Burning technologies of composite fuels is characterized by positive economic and environmental effects. That is why consistent patterns and necessary conditions have been experimentally discovered for the ignition of typical composite fuel consists of filter cakes with 10% of typical MSW (rubber, or wood, or plastic) and 5% of used motor oil under heating conditions similar to those of fuel combustion in boiler furnaces.

(2) The fuel compositions under study (85% of filter cakes + 10% of MSW + 5% of used oil) were used as examples to experimentally validate sustainable ignition and combustion of composite fuel droplets up to their complete burnout in the conditions typical of conventional boiler furnaces. A software system for high-speed video recording outlined the main interdependent stages of process: heating; moisture evaporation; thermal decomposition of solid combustible components (MSW and coal); formation of combustible mixture; gas-phase ignition and burnout; heating of the solid combustible residue; heterogeneous ignition and combustion of the latter.

(3) The values of the guaranteed ignition delay times for droplets with a size (diameter) of about 2 mm have been established for the composite fuel compositions under study in a wide range of the ambient temperature variation 600–1000 °C. The minimum values of ignition delay times are about 3 s, the maximum values are about 15 s. The maximum difference in ignition delay times of fuel compositions with different components is less than 20% at the ambient temperature 600–1000 °C. An approximation equation $t_d = f(T_g)$ has been derived for a rapid evaluation of mean ignition delay time values of composite fuel droplets (filter cakes 85% + MSW 10% + oil 5%).

The obtained results serve as a foundation for the development of joint routines by neighboring regions (those with a high level of solid and liquid fossil fuel extraction, and those with a high level of social advancement) to implement high-potential technologies of burning composite fuels prepared from industrial and municipal waste at thermal power plant. One of the benefits of such technology is a possibility to optimize the modes of the main process equipment operation by varying the compositions of composite fuels and the concentration of combustible components. The new technology is the basis for countries not recycling MSW other than by burial at disposal sites to implement a waste management strategy. During the 15–25 years of transition from waste burial to re-use and recycling, it is essential to minimize the volumes of non-recycled waste disposal. Within this time, the proposed waste management strategy will, on the one hand, reduce the amount of waste to be buried and decrease the consumption of high-grade coal for heat and electricity generation, and on the other hand, will eliminate interim steps involving the construction of costly incineration plants which will be in demand for a relatively short period of time. The analysis of three regions of the Russian Federation, taken as an example, established that complete replacement of coal by a composite fuel with an equivalent energy output will save 10 Mt of solid fossil fuels a year in the course of 25 years (during the period of transition to a new system of waste management with a high share of recovery and re-use of MSW). During the same time interval, about 315 Mt of filter cakes, 53 Mt of MSW, and about 2.6 Mt of used oil will have been disposed of. The proposed measures will completely resolve the issue of recovering the used oils, liquid combustible oil production and oil refining waste, accumulated by 2017, and annually produced coal processing waste, as well as reduce the amount of filter cakes accumulated by 2017 by 84%. Moreover, adding MSW to the fuel composition will eliminate the problem of its disposal until the transition has been effected to a new system of waste management with a high share of MSW recovery and re-use, and reduce the volumes of MSW that have been accumulated by 2017 at landfill sites by 36%.

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