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CHAPTER 3

TECHNOLOGICAL ASPECTS OF PRODUCING REFUSE DERIVED FUEL

ABSTRACT

The involvement of municipal solid waste in the energy balance of Ukraine is one of the important ways of replacing fossil fuels and solving environmental problems related to the disposal of waste in proving ground and landfills.

The purpose of the research is to find a rational composition of an alternative solid fuel for burning in cogeneration power plants and an energy-efficient technology for its production.

The object of research is alternative solid fuel (RDF – refuse derived fuel) based on combustible components of municipal solid waste.

The kinetics of convective drying of RDF of different composition depending on the temperature and rate of heat carrier was investigated. The relative and kinetic coefficients of drying, generalized drying rates for each drying period and the calculated duration of the drying process for different compositions of RDF were determined.

The thermal decomposition of various refuse derived fuel mixtures was investigated using thermal analysis methods. Temperatures of dehydration, thermal decomposition of organic and mineral substances are determined. Data were obtained on the content of water, organic and mineral substances, and ash in RDF of various compositions. The rates of thermal destruction in different phases of heating were calculated, the kinetics of decomposition and heat generation during the thermal decomposition of organic substances were compared. The calorific value of RDF of different composition was determined by the method of calorimetry.

KEYWORDS

Municipal solid waste, technology, RDF, drying, thermal analysis, calorific value of solid fuel.

Among the technologies of energy use of municipal solid waste, the most common and one of the most effective is the technology of burning this waste in cogeneration plants with the production of electrical and thermal energy.

Obtaining highly efficient composite fuels based on solid household waste is of considerable scientific interest as it requires the development of appropriate energy-saving technologies.

Analysis of technological stages of RDF (refuse derived fuel) production showed that all stages of production are energy consuming. The drying stage is characterized by particularly high energy consumption. Drying processes account for about 40–50 % of the total energy consumption, and in cases of drying municipal solid waste (MSW) with high humidity, the consumption increases to 70 %. Low energy efficiency is characteristic of the stages of raw material preparation, which affects the energy efficiency of production in general and the cost of fuel.

Therefore, research and identification of factors influencing the processes of raw material preparation and drying will improve the quality of fuel and ensure a sustainable year-round production cycle. Study of methods for preparing raw materials for drying and modeling the kinetics of dehydration in drying machines will allow to develop ways and directions of energy saving.

Increasing the calorific value of composite fuel based on MSW requires combining components, the physical and chemical properties of which are not sufficiently studied. Combustion of RDF also requires knowledge of kinetics of thermal decomposition of components and generation of heat.

The analysis of the results of research into various aspects of the proposed technology for burning fuel from municipal solid waste in cogeneration plants indicates the need to carry out a complex of research to components of this technology and, above all, technologies for obtaining RDF and its burning.

Simultaneously with the involvement of municipal solid waste in the energy industry, environmental problems related to the disposal of waste in proving ground and landfills, which leads to catastrophic pollution of air, soil, surface and groundwater, will be solved. Due to the expected decrease in the number of proving ground and landfills, the volume of greenhouse gas emissions will decrease.

3.1 ANALYTICAL REVIEW AND ANALYSIS

3.1.1 MUNICIPAL SOLID WASTE AND FUEL FROM IT

Incorrectly utilized municipal solid waste (MSW) harms the environment and human health, and also takes up too much land.

Traditional methods of disposal and treatment of MSW include landfill, incineration and biological treatment. However, these methods have certain disadvantages [1, 2]. Even well-planned and managed landfills can become problematic from an environmental and public perception perspective [3]. The European Commission requires reductions in landfilling to prevent or reduce negative impacts on the environment, including pollution of surface water, groundwater, soil and air, as well as the global environment, including the greenhouse effect [4].

One of the perspective and important ways to solve this problem is to use municipal solid waste as fuel.

Fuel from waste (RDF) – this is an alternative solid fuel that contains the combustible part of household or industrial harmless waste remaining after the separation of secondary raw materials [5]. Secondary raw materials usually make up 20–40 mass % of MSW [6]. The ratio of RDF production to MSW is about 24 %, which means that only 240 kg of RDF can be extracted from one ton of municipal waste [7]. RDF is a cheaper fuel than conventional fossil fuels, and the higher calorific value of dried RDF depends on the composition of the components and ranges from 17–25 MJ/kg. The composition mainly includes polymer materials that cannot be recycled, paper, cardboard, textiles, packaging waste, wood waste, etc. [8]. Unlike direct MSW incineration, RDF incineration has higher efficiency due to higher calorific value and less negative impact on the environment.

One of the main indicators that limit the use of RDF is greenhouse gas emissions. When coal to replace on RDF, the water content should be less than 15 %. In this case, the net emission reduction is 0.4 tons of CO_2/ton of coal [9]. In most cases, RDF is co-fired with biomass to reduce the total amount of recorded CO_2 emissions, as biomass is considered carbon neutral [10, 11].

Such fuel is usually used in cement furnace, boilers and for electricity production [5]. Electric power stations and cement plants burn RDF mainly by blending it with coal or biomass [19, 20, 21]. According to reports [12], in Europe, between 30 % and 60 % of fossil and alternative fuels have been replaced by RDF in cement and waste processing plants. In 2015, RDF consumption in Europe was 12 million tons [13]. Other energy carriers, such as fuel oil and gases, are obtained from RDF through pyrolysis and gasification processes [14].

If the fuel passes the test and meets the requirements set forth in the DSTU EN 15359 [15], it is classified as a solid recovered fuels (SRF). The standard states that SRF is produced from non-hazardous waste. Raw materials for fuel can be industrial waste, municipal solid waste, industrial waste, commercial waste, construction and demolition waste, sewage sludge, etc. The goal of producing solid recovered fuel is to use it to produce energy with the highest possible energy efficiency. This is facilitated by a clearly defined system of classification and specification.

The classification system is based on three main characteristics – economic (lower calorific value), technical (chlorine content) and environmental (mercury content). The characteristics are chosen to give the interested party an immediate but simplified view of the fuel in question. Only fuel derived from non-hazardous waste that meets European SRF standards can be classified as SRF.

The classification (**Table 3.1**) for SRF is based on limit values for three important fuel characteristics:

a) average value of lower calorific value (ar);
b) average value of chlorine content (d);
c) median and 80th percentile for mercury content (ar).

Each characteristic is divided into 5 classes. For the SRF must be assigned a class number from 1 to 5 for each characteristic. The combination of class numbers makes up the class code. The features are of equal importance, so no class number defines the code. The classes were defined as a tool for the identification and pre-selection of SRF.

Table 3.1 Classification system for solid recovered fuels

Classification characteristic	Statistical measure	Unit	Classes				
			1	**2**	**3**	**4**	**5**
Net calorific value (NCV)	Mean	MJ/kg (ar)	≥25	≥20	≥15	≥10	≥3
Chlorine (Cl)	Mean	% (d)	≤0.2	≤0.6	≤1.0	≤1.5	≤3
Mercury (Hg)	Median 80^{th} percentile	mg/MJ (ar) mg/MJ (ar)	≤0.02 ≤0.04	≤0.03 ≤0.06	≤0.08 ≤0.16	≤0.15 ≤0.30	≤0.50 ≤1.00

*Note: *Median is a number that "divides" "in half" an ordered collection of all sample values, i.e. the average value of a variable characteristic, which is in the middle of a series arranged in ascending or descending order of the characteristic.*
***Percentile is the value that a given random variable does not exceed with a fixed probability given as a percentage. Thus, the n-th percentile is the same as n/100*

3.1.2 TECHNOLOGIES OF OBTAINING RDF/SRF

Fuel from waste is obtained according to the requirements of the end user. According to the composition, RDF is divided into two types – those that don't contain organic wastes and those that contain it. In the production of the first type of RDF, metals and inert substances are removed from municipal solid waste, and the organic fraction is screened and composted. A product with a high calorific value is obtained, which mainly consists of plastic, paper and textiles [16]. Another type of RDF is made from the same residual waste composition, but includes organics that become part of the RDF through a process of "biostabilization" or "biodrying". This process allows the organics to go through a partial composting process without adding moisture. Since composting is an exothermic process, the heat from partial composting dries out the material and oxidizes the decaying organic fraction while keeping the other organic matter intact. Then this biostabilized material is mechanically processed through several grading steps to achieve the specific size required to produce the desired RDF. The level of mechanical processing depends on the fuel specifications for the combustion technology used by the RDF end user [16, 17].

In terms of physical characteristics, RDF can be manufactured as bulk or granular materials [17]. This depends on several factors, including the proximity of the production unit to the final consumer, the need to store the material before its use and the type of power system of the incineration facility [16].

Municipal solid waste processing technologies with the production of RDF can be conditionally divided into four groups according to the characteristics of the raw materials (**Table 3.2**) [18]. Given the number of potential products, the type of specific technology used to convert solid waste into RDF may vary from one location to another [19].

Technologies for the direct production of RDF/SRF include the following main stages: sorting, grinding, separation, mixing, drying, granulation and packaging. In general, the technological scheme of fuel production from waste is presented in **Fig. 3.1** [20].

Table 3.2 Brief description of key technologies of waste processing [18]

Production technology **Features**	**Clean material recovery facility**	**Dirty material recovery facility**	**Mechanical biological treatment**	**Mechanical heat treatment**
Feedstock	Mixed/Commingled recyclables (Municipal & Commercial)	Mixed Residual Waste (Mainly C&D municipal & commercial waste)	Mixed putrescible residual waste (mostly municipal)	Mixed residual wastes (Municipal and Commercial)
Product/outputs	– Separated recyclable materials: paper, cardboard, plastics, glass, steel and aluminum. – Glass fines for potential further processing. – Light residuals-potential RDF. – Residual to landfill	– Separated recyclable materials including paper, cardboard, plastics, glass, steel, aluminum, masonry product, soil, timber. – RDF. – Residuals to landfill	– Low grade soil amendment/compost. – Recyclable material including rigid plastics, steel and aluminum. – RDF. – Residuals to landfill	– Organic rich fiber-low grade soil amender, fuel. – RDF from inorganic fraction-to thermal process. – Recyclables (low grade)

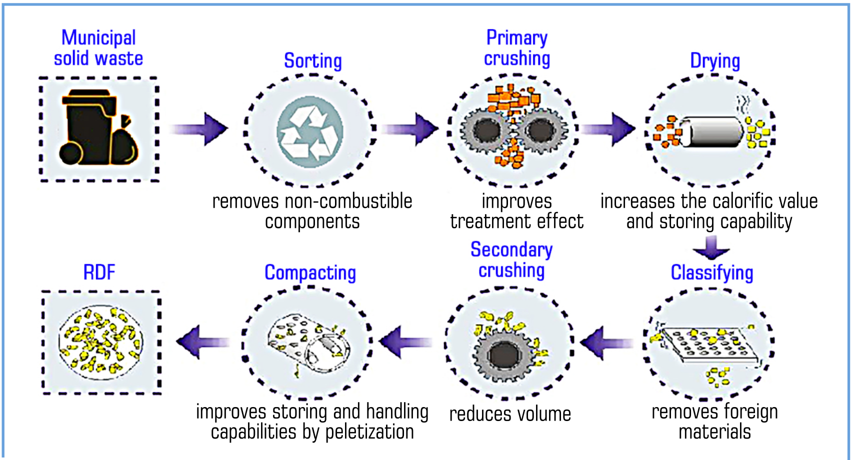


Fig. 3.1 RDF production technology

The steps and necessary equipment for the production of RDF are given below [17]:

1. *Waste reception, sampling, manual sorting and bag opening area:* MSW arriving by appropriate transport is unloaded for sampling, manual sorting of large components and transported to bag opening machines.

2. *Sorting* includes the separation of municipal solid waste into biodegradable, glass, textiles, paper, plastic, leather and rubber, metals and other hazardous municipal solid waste, as well as

inert materials. Secondary raw materials are extracted, which are then processed. The main components used in the production of RFD include directly combustible materials.

3. *Primary crushing:* the two-shaft primary crusher is designed for crushing residual waste to a size of less than 100 mm.

4. During *drying*, the material is dehydrated. This can happen both under the influence of solar radiation and in special dryers. This process increases the calorific value of the material, reduces the mass, and also increases the ability to store fuel for a long time.

5. A rotary drum is used *to separate* the material by size. Separation usually occurs in two or more stages of the process. This is done by passing the waste through drum screens, most often roller drums with different hole sizes. At various stages of processing, conveyor belts are attached to conveyor belts and positioned at an angle to allow oversized materials to pass over them. Remaining material is thrown onto the conveyor belt, which transports the material for further processing.

Magnetic separators are used to remove any metals from remaining material. The device uses eddy currents that create a powerful magnetic field that makes separation possible. The eddy current separator is applied to a conveyor belt that transports a layer of mixed waste. At the end of the conveyor belt is an eddy current rotor.

Fans on the air separation stage are used to create a column of air moving upwards. Light materials are blown up, and dense materials fall. Air carrying lightweight materials such as paper and plastic bags enters a separator where these items fall out of the air stream. The quality of separation at this stage depends on the strength of air currents and the method of introducing materials into the column. Moisture content is also critical, as water can weigh down some materials or cause them to stick together.

6. The two-roller secondary chopper is designed for *secondary crushing* of material to a thickness of less than 50 mm. After that happens finer crushing to an RDF particle size of less than 25 mm.

7. *The compacting* of material is intended for the production of fuel pellets with a diameter of 16–25 mm by extrusion. The crushed material is fed into the granulator by gravity. The roller pushes the material through holes of the die and extrudes the material. The knife under the press die can adjust the size of the granules. Then the granules are cooled on a cooling conveyor and sent to storage.

The choice of municipal solid waste processing technology directly depends on the characteristics of the waste. The defining characteristics are the morphological, fractional and chemical composition, density, heat of combustion and moisture content of municipal solid waste [11]. These characteristics depend on the place and time of waste generation. The average annual morphological composition for large cities of Ukraine is presented in **Fig. 3.2** [22].

The largest share is food waste, which has high moisture content and low calorific value, so it is not recommended to use it for the production of RDF. If the non-combustible components to separate, it is possible to predict the composition of fuel that can be obtained in large cities of Ukraine. In this case, RDF can contain polymer materials, paper and cardboard, textiles, wood, leather and rubber (**Fig. 3.3**).

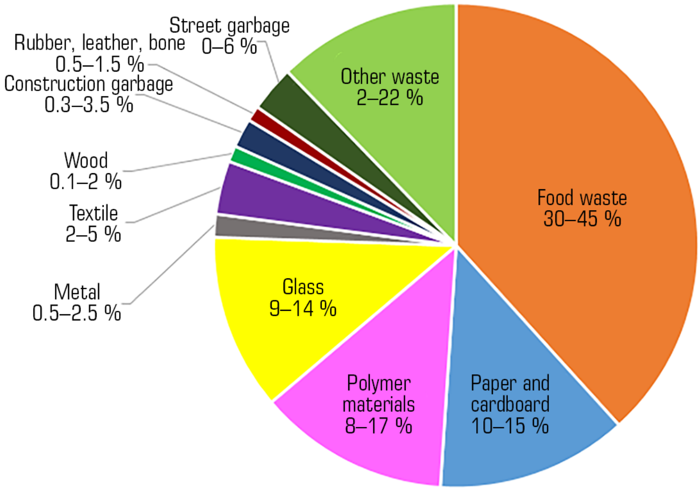


Fig. 3.2 Morphological composition of MSW for large cities of Ukraine

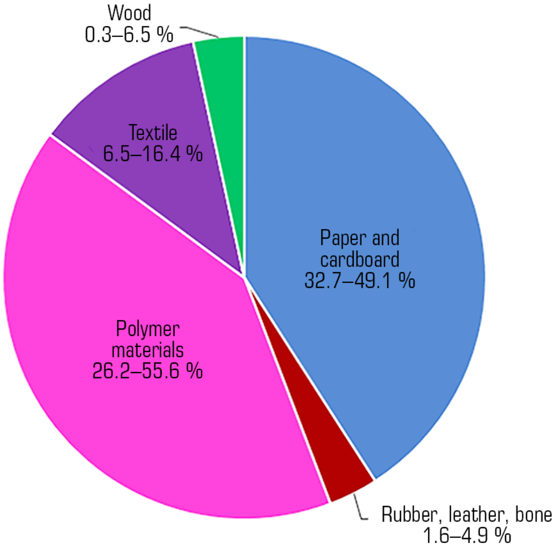


Fig. 3.3 Average morphological composition of combustible solid waste, which can be raw materials for RDF

Analysis of technological stages of RDF production showed that all stages of production are energy consuming. The drying stage is characterized by particularly high energy consumption. Drying processes account for about 40–50 % of the total energy consumption, and in cases of drying municipal solid waste with high humidity, the consumption increases to 70 %. Low energy efficiency is characteristic of the stages of raw material preparation, which affects the energy efficiency of production in general and the cost of fuel. Thus, about 10–20 % of the total energy consumption is spent on crushing.

Granulation is the final stage of solid fuel production and 10–30 % of total energy is spent on its implementation. Granulation costs depend on the physico-mechanical and physico-chemical properties of the fuel components, pressure and temperature in the compaction zone. Due to the insufficient amount of experimental data on the physico-chemical and physico-mechanical properties of municipal solid waste, there may be energy overspending during the production of fuel from this type of raw material.

Therefore, research and identification of influencing factors on raw material preparation and drying processes will improve fuel quality and ensure a stable year-round production cycle. The study of methods of preparing raw materials for drying and modeling the kinetics of dehydration in drying devices will allow to develop ways and directions of energy saving.

Increasing the calorific value of composite fuel based on MSW requires combining components, the physical and chemical properties of which are not sufficiently studied. Combustion of RDF also requires knowledge of kinetics of thermal decomposition of components and generation of heat.

The efficiency of using RDF is determined by obtaining its characteristics during the combustion process. The results of the thermal analysis, as well as the determination of the calorific value, are important.

3.2 STUDY OF REGULARITY OF RDF CONVECTIVE DRYING

3.2.1 PREPARATION OF MUNICIPAL SOLID WASTE FOR DRYING

1. The composition of municipal solid waste in Ukraine was analyzed, among which RDF was allocated (40 % of the total mass of waste). The main components are highlighted: wood, textile materials, polymer materials, paper, cardboard, leather, rubber, bones.

2. 4 types of mixtures are made from 5 groups of materials, including: wood (5 – 23 %), textile materials (12 – 16 %), polymer materials (25 – 50 %), paper, cardboard (25 – 50 %), leather, rubber, bones (3 – 4 %) (**Table 3.3**).

3. The initial moisture content of the obtained mixtures was determined, which is from 5 to 6 %, which depends on the composition.

4. The mixtures were dried to a completely dry mass at a coolant temperature of 150 °C and duration of 4 hours for the subsequent uniform moistening of these mixtures.

Table 3.3 Composition of RDF (100 g)

The name of the component RDF	Composition of mixtures, %/g			
	I mixture	II mixture	III mixture	IV mixture
Wood (pine)	23	5	5	5
Textile materials (cotton, synthetic fabrics)	12	15	16	16
Polymer materials (PET bottles, polyethylene film)	31	40	50	25
Paper, cardboard	31	37	25	50
Skin, rubber, bones	3	3	4	4

5. Before conducting research, it is possible to determine the initial moisture content of RDF. The RDF mixture is placed into boxes and dried in a laboratory dryer for 5 hours at a temperature of 105 °C. After drying, the boxes are removed from the laboratory dryer and placed in a desiccator to cool for 15–30 minutes. Cooled boxes with material are weighed in a closed state on scales.

The moisture content of the material relative to the mass of the dry substance is calculated as a percentage:

$$W = \frac{m_2 - m_3}{m_3 - m_1} \cdot 100\ \%, \tag{3.1}$$

where m_1 – mass of the empty box (with a lid), g; m_2 – mass of the box with the research sample before drying, g; m_3 – mass of the box with research sample after drying, g.

6. Research on the drying of RDF samples begins with setting the drying mode on a convective stand [23], then the sample is placed on a grid of scales in the drying chamber, and a computer program for collecting and processing information is turned on, which continuously records the time and change in the mass of the sample, the heat carrier temperature and the temperature in the middle of sample.

7. After drying, RDF samples are removed from the drying chamber and analyzed for quality characteristics and the final moisture content of the material is determined according to item 5 and formula (3.1).

8. After determining the absolutely dry mass of the sample, the computer program determines the current moisture content of the material W during drying and calculates and plots drying curves and drying rates: $W=f(\tau)$, $dW/d\tau=f(W)$.

9. The characteristics are calculated using a specially developed program "Sooshka".

10.1. Kinetic of the drying process:

$$W(t) = \frac{G(t) - G_{a.d.}}{G_{a.d.}} \cdot 100\ \%, \tag{3.2}$$

where $G(t)$ – calculations of mass of sample, g; $G_{a.d.}$ – absolutely dry mass, g.

10.2. The drying speed is determined:

$$N = \frac{dW}{d\tau}. \tag{3.3}$$

10.3. The drying temperature coefficient is an estimate of the derivative of the average temperature of the sample from the moisture content:

$$b = \frac{dt_{aver}}{dU}, \tag{3.4}$$

where $U = W/100$ – moisture content of the sample, %; t_{aver} – calculated as the average value of the temperature calculation on the surface and in the sample material, °C.

10.4. Rebinder number is equal to the ratio of the amount of heat expended to heat the body to the amount of heat to evaporate moisture in an infinitesimally small period of time:

$$Rb = \frac{c}{r} b, \tag{3.5}$$

where c – specific heat capacity of the material, kJ/(kg·°C); r – specific heat of phase transformation, kJ/kg.

10.5. The heat flux per unit surface of the sample is calculated from the ratio:

$$q(\tau) = rg\left(\frac{dU}{d\tau}\right)(1 + Rb), \tag{3.6}$$

where $g = G_{a.d.}/S_m$ – the ratio of the mass of absolutely dry body to the surface of the material.

10.6. The heat transfer coefficient is determined by the formula:

$$\alpha = \frac{1000 \cdot q(\tau)}{t - \theta}, \tag{3.7}$$

where t – heat carrier temperature; θ – sample temperature.

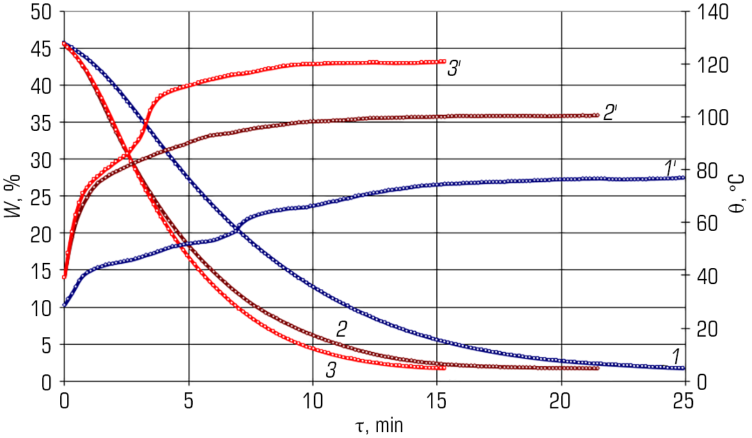
3.2.2 RESEARCH OF DRYING MODES OF RDF

The study of drying modes is carried out with the determination of the influence of the following factors: the heat carrier temperature (80–120 °C), the speed of movement of the heat carrier (1.5–2.5 m/s) and the composition of the mixture (No. 1–4).

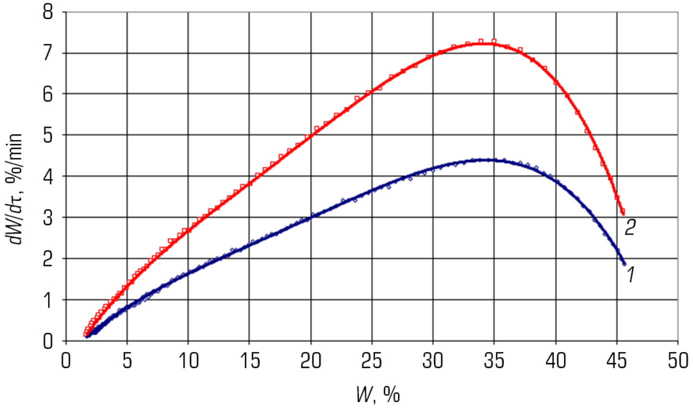
The influence of heat carrier temperature on the kinetic of the drying process. When the temperature of the heat carrier increases from 80 to 120 °C, the drying duration is accelerated by 56 %.

eating of the material in a layer of 15 mm to the final temperature takes place within 10–15 minutes. The material at a heat carrier temperature of 80 °C heats up to a temperature of 78.8 °C, at a temperature of 100 °C – 98.9 °C, at a temperature of 120 °C – 119.8 °C (**Fig. 3.4**).

The process of drying municipal solid waste is in 2 stages: a period of heating up to the maximum drying speed and a period of falling drying speed (**Fig. 3.5**).



⬡ **Fig. 3.4** Effect of heat carrier temperature on the kinetics of the RDF drying process: $V=2.5$ m/s, $d=10$ g/kg dry air, $\delta=15$ mm, mixture No. 1: 1, 1′ – 80 °C; 2, 2′ – 100 °C; 3, 3′ – 120 °C



⬡ **Fig. 3.5** Influence of heat carrier temperature on RDF drying speed $V=2.5$ m/s, $d=10$ g/kg dry air, $\delta=15$ mm, mixture No. 1: 1 – 80 °C; 2 – 120 °C

To compare the effect of coolant temperature on the drying speed of RDF mixtures, heat carrier temperatures of 80 and 120 °C were selected. The maximum drying speed increases by 1.82 times when the heat carrier temperature increases (**Fig. 3.5**).

The influence of the heat transfer speed on the kinetics of the drying process. Conducted studies of the effect of temperature on the kinetics of drying process showed that increasing the heat carrier temperature to 120 °C significantly intensifies the drying process. Therefore, the effect of the speed of movement of the heat carrier on the kinetics of the drying process is carried out at a temperature of the heat carrier of 120 °C. To compare the speeds of movement of heat carrier, speeds of 1.5 and 2.5 m/s were selected.

Increasing the heat carrier speed from 1.5 to 2.5 m/s reduces the drying time by 6 minutes or by 38 %. The heating temperature of the material at a heat carrier speed of 1.5 m/s is 115 °C, which is 4.8 °C lower than the heat carrier speed of 2.5 m/s (**Fig. 3.6**).

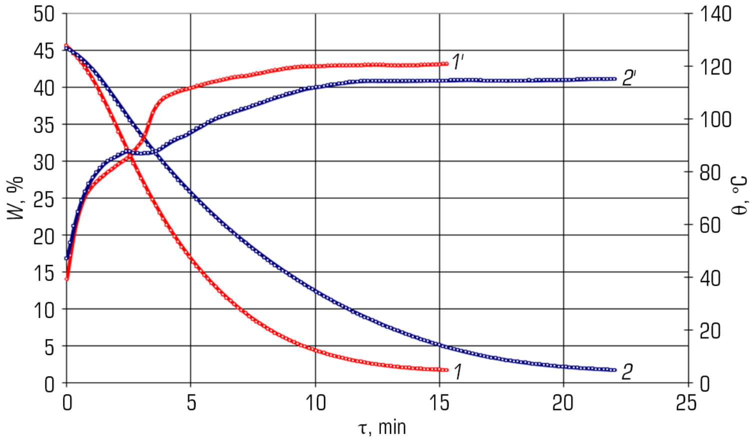


Fig. 3.6 The influence of the heat carrier speed on the kinetics of the RDF drying process $t=120$ °C, $d=10$ g/kg dry air, $\delta=15$ mm, mixture No. 1: 1, 1′ – 2.5 m/s; 2, 2′ – 1.5 m/s

The influence of the RDF mixture composition on the kinetics of drying process. According to **Table 3.3**, there are 4 types of RDF mixtures that can significantly affect the kinetics of the drying process.

To study the kinetics of the drying process, it is possible to choose the drying mode studied earlier: coolant temperature 120 °C, coolant movement speed 2.5 m/s.

The analysis of the influence of the composition of RDF mixture on the kinetics of the drying process showed that it is appropriate to separate the comparison of mixtures No. 1, 2, 3 and No. 1, 4. The duration of drying of mixtures No. 1, 2, 3 (with the content of polymeric materials from 31 to 50 %) is 16 minutes, but the heating of the material occurs in different ways, which is connected with the composition of solid fuel. Thus, the final heating temperature of mixture No. 1 is 119.8 °C, mixture No. 2 is 116.7 °C, and mixture No. 3 is 117.6 °C (**Fig. 3.7**).

The influence of mixtures No. 1, 4 (with cardboard content from 31 to 50 %) on the kinetics of the drying process was also analyzed (**Fig. 3.8**). When changing mixtures from No. 1 to No. 4, the duration of drying increases by 28 %.

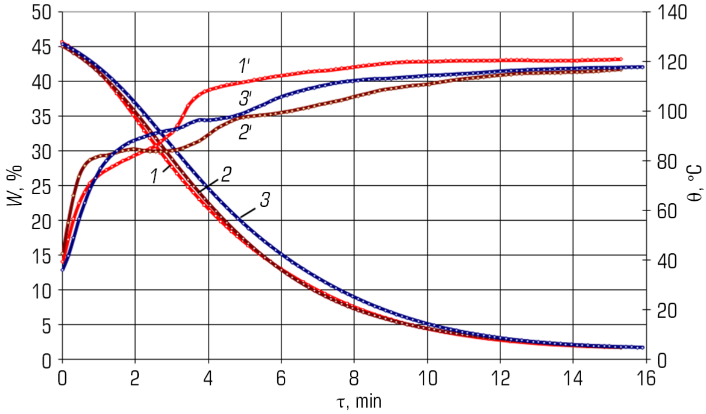


Fig. 3.7 Influence of the composition of mixture (1, 2, 3) on the kinetics of the RDF drying process t=120 °C, V=2.5 m/s, d=10 g/kg dry air, δ=15 mm: 1 – mixture No. 1; 2 – mixture No. 2; 3 – mixture No. 3

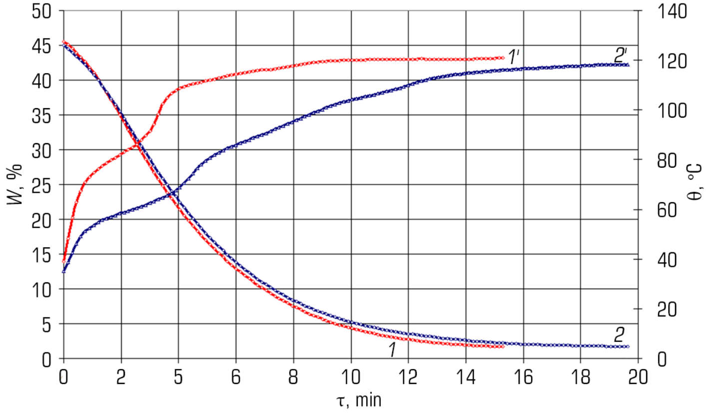


Fig. 3.8 Influence of the composition of the mixture (1,4) on the kinetics of the RDF drying process t=120 °C, V=2.5 m/s, d=10 g/kg dry air, δ=15 mm: 1 – mixture No. 1; 2 – mixture No. 4

3.2.3 RESEARCH OF HEAT AND MASS EXCHANGE PROCESSES DURING DRYING RDF

The kinetics of heat exchange during drying can be fully revealed by the data of the kinetics of moisture exchange.

Value of magnitude $d\bar{t}/d\bar{W}$ determines the change in the average temperature of the dried material per unit of change in its average humidity over an infinitesimally small period of time and is called the drying temperature coefficient:

$$b = \frac{d\bar{t}}{d\bar{W}}. \tag{3.8}$$

Magnitude b is a function of integral humidity $b = f\left(\bar{W}\right)$.

Based on the ratio of RDF heating and moisture evaporation, as can be seen from **Fig. 3.9**, the most appropriate drying mode is 100 °C.

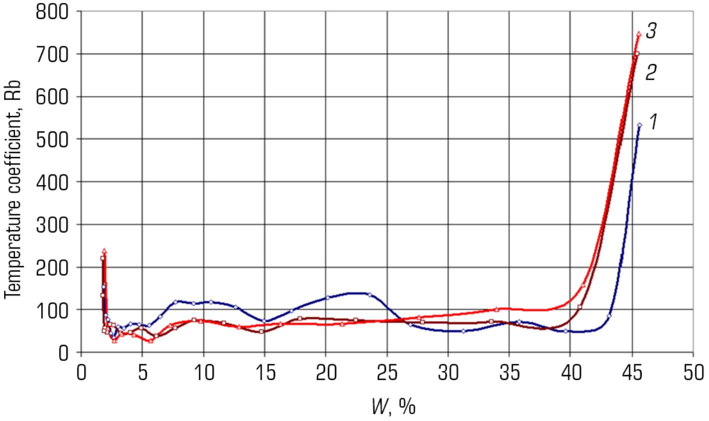


Fig. 3.9 Change in the temperature coefficient depending on the moisture content of the material and the heat carrier temperature during the RDF drying process $V=2.5$ m/s, $d=10$ g/kg dry air, $\delta=15$ mm, mixture No. 1: 1 – 80 °C, 2 – 100 °C, 3 – 120 °C

General variable $b\left(\bar{c}/r\right)$ is an integral characteristic of the kinetics of the drying process. It determines the ratio heat amount of the heating of the material during drying and to the evaporation of moisture in an infinitesimally small period of time. This basic drying criterion is called the Rebinder number:

$$Rb = b\frac{\bar{c}}{r} = \frac{\bar{c}}{r}\left(\frac{d\bar{t}}{d\bar{W}}\right). \tag{3.9}$$

Rebinder criterion (**Fig. 3.10**) shows that heat is spent on heating the material at the beginning of RDF drying, then drying occurs with simultaneous heating and evaporation of moisture from the material to a moisture content of 3 %. At a humidity of 3 %, heat is inefficiently used, as the material is heated sharply with a decrease in the evaporation of moisture from the material.

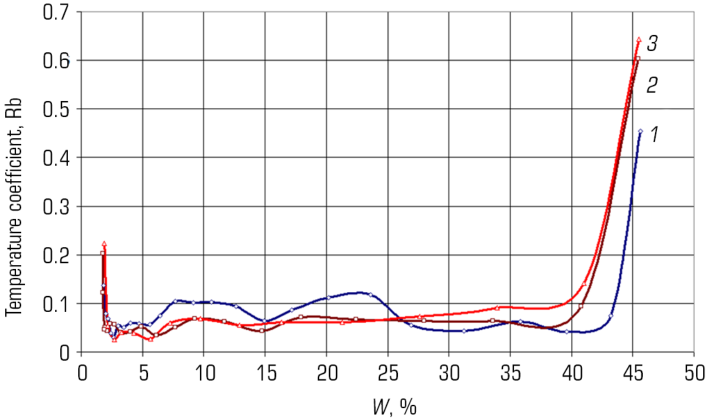


Fig. 3.10 Change of Rebinder criterion depending on material humidity and heat carrier temperature during RDF drying $V=2.5$ m/s, $d=10$ g/kg dry air, $\delta=15$ mm, mixture No. 1: 1 – 80 °C, 2 – 100 °C, 3 – 120 °C

The heat supplied to the material is spent on heating the material and on the evaporation of moisture. The density of the heat flow spent on evaporation is calculated by the intensity of moisture exchange $m(\tau)$ from the equation:

$$q_{evap} = rm(\tau) = rg\frac{d\overline{W}}{d\tau}. \tag{3.10}$$

The heat flow density for heating the material is determined by the ratio:

$$q_{heat} = cg\frac{d\overline{t}}{d\tau}, \tag{3.11}$$

where c – heat capacity of the material.

In accordance with the law of conservation of energy, the specific heat flow per unit surface of the body is equal to:

$$q(\tau) = rg\frac{d\overline{W}}{d\tau} + \overline{c}g\frac{d\overline{t}}{d\tau} = gr\frac{d\overline{W}}{d\tau}\left[1 + \frac{\overline{c}}{r}\frac{d\overline{t}}{d\overline{W}}\right]. \tag{3.12}$$

The heat flux density reaches its maximum value when the material is heated to the maximum value (**Fig. 3.11**). During the removal of moisture from the material, the heat flux density decreases.

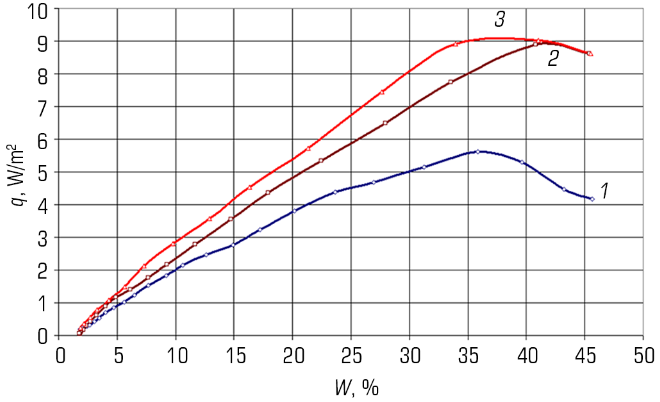


Fig. 3.11 Change in heat flux from material humidity and temperature of the heat carrier in the process of drying RDF V=2.5 m/s, d=10 g/kg dry air, δ=15 mm, mixture No. 1: 1 – 80 °C, 2 – 100 °C, 3 – 120 °C

The main conclusions based on the results of the experiments:

1. When the heat carrier temperature increases from 80 to 120 °C, the duration of drying decreases by 56 %.
2. Increasing the speed of heat carrier from 1.5 to 2.5 m/s at a temperature of 120 °C reduces the drying time by 6 minutes or by 38 %.
3. When changing the composition of the RDF mixture with a high content of polymer materials from 31 to 50 % to the RDF mixture with a high content of paper and cardboard from 31 to 50 %, the drying time increases by 28 %.
4. The study of heat and mass exchange processes during drying of RDF, in particular the temperature coefficient, the Rebinder number and the change in heat flow from the moisture content of the material when the temperature of the heat carrier changes from 80 to 120 °C, indicated the feasibility of drying above 100 °C. The maximum value of the heat flow at modes 100, 120 °C has a value of 9 W/m^2, which is 1.63 times higher than the drying mode 80 °C.

3.3 RDF THERMAL ANALYSIS

The efficiency of using RDF is ultimately determined during the combustion process. However, it is possible to predict fuel characteristics with the results of thermal analysis. Thermogravimetry and differential thermal analysis contribute to expanding knowledge on the kinetics of thermal destruction and heat generation [24].

Research into the RDF characteristics is actively carried out around the world [11, 25, 26, etc.]. However, there are problems associated with quality assurance and accurate determination of the thermal characteristics of the fuel due to its heterogeneous composition. Also, fuel from waste of different composition has different kinetics of thermal destruction [11, 25–27]. Therefore, each type of RDF requires a study of thermal characteristics to predict its quality.

Combustion of RDF also requires a comprehensive study of its thermotechnical characteristics, in particular, the investigation of physicochemical properties, kinetics of thermal decomposition of the components and heat generation.

3.3.1 RESEARCH TECHNIQUE FOR THERMAL DECOMPOSITION OF RDF

Derivatography is one of the most informative methods of studying the thermal decomposition of solid fuels. It makes it possible to determine the stages and temperature ranges of decomposition, the type of thermal effects and the depth of structural and chemical transformations of the fuel.

The derivatography, which combines thermogravimetry (TG) with classical differential thermal analysis (DTA), has found wide application in scientific research. It allows obtaining information about the behavior of individual substances and composites under conditions of programmed heating. Qualitative and quantitative assessment of the processes occurring during heating of samples is carried out using the curves of changes in sample temperature (T), its mass (TG), differential thermogravimetry (DTG), which is a derivative of the TG, and DTA curve. The DTA curve represents the temperature difference between the sample and the inert material in the form of the difference in thermoelectromotive forces of thermocouples. It allows one to identify the thermal processes occurring in the sample when it is heated. The temperature of the peaks of thermal effects (DTA) is higher than the temperature of the corresponding maximums of the rate of mass change (DTG) due to the existing thermal resistance of the sample material and the crucible walls.

Thermogravimetric studies were carried out in a derivatograph "Q-1000" manufactured by MOM (Hungary), modernized at the Institute of Engineering Thermophysics of the NAS of Ukraine. The block diagram of a modernized derivatograph for studying the thermal destruction of solid fuels is shown in **Fig. 3.12**.

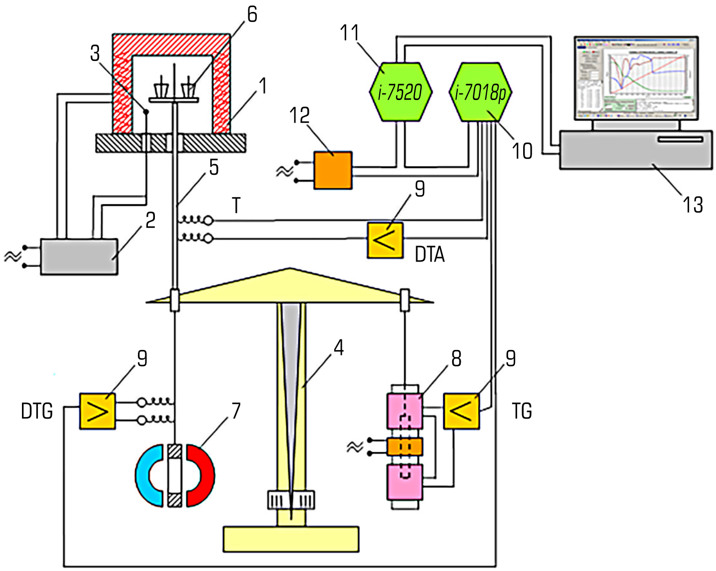
The derivatograph consists of a furnace, a scales unit, measurement and information processing units. The set temperature is maintained in furnace 1 using programmer 2 and controlled by thermocouple 3. A scales unit includes analytical scales 4 with devices for changing sensitivity and absorbing vibrations. A hollow ceramic rack 5 is suspended on one side of the scales rocker, the upper end of which is inserted into the furnace.

In the upper part, the rack has a comb with built-in junctions from two differential thermocouples. The first (working) thermocouple is designed to measure the temperature of the sample (T) during the heating process. A crucible with an inert substance is placed on the junction of the second thermocouple. The temperature difference between the sample and the inert substance is registered in the form of a differential electromotive force (DTA).

The electromagnetic coil of the device 7 and the ferrite rod of the device 8 are placed on the other side of the scales rocker. Device 8 is made in the form of a differential transformer with a ferrite rod in the middle, designed to register the change in the mass of the sample (TG). Device 7 consists of an electromagnetic coil in the form of a frame, which is suspended in the field of a permanent magnet. In the frame, a voltage is generated proportional to the rate of change of the mass of the sample (DTG) when moving in a uniform magnetic field.

Information about the change in mass and temperature of the sample is sent to the analog-to-digital converter 11 and transmitted to the personal computer 13 using the interface converter 12.

Control of the collection and processing of information from the derivatograph "Q-1000" was carried out using the "Derivatograph" computer application program created in the Delphi programming language.



1 – furnace; 2 – temperature programmer in the furnace;
3 – thermocouple of temperature control in the furnace; 4 – scales;
5 – ceramic rack; 6 – sample; 7 – device for measuring the rate of moisture removal;
8 – device for measuring the change in mass of the sample; 9 – signal amplifier;
10 – analog-to-digital converter; 11 – interface converter; 12 – power supply; 13 – computer

Fig. 3.12 Block diagram of the modernized derivatograph "Q-1000"

All materials (combustible components of MSW) were stored for a long time in the laboratory at a relative humidity of 40 % and a temperature of 20 °C. Before the study, they were crushed to a particle size of ≤0.5 mm. Almost all samples had equilibrium moisture content.

The thermal decomposition of the samples was studied by heating them from ambient temperature to 1000 °C at a constant rate (7.4 K/min) with a scale resolution of 0.5 mg. Fuel samples weighing 50–70 mg were placed into an open conical platinum crucible. Destruction took place under static conditions of a gas environment in the zone of thermal decomposition reactions, that is, in a gas atmosphere formed during the thermal decomposition of organic substances in the absence of air movement in the area of the crucible.

3.3.2 RESULTS OF THE DERIVATOGRAPHIC STUDIES OF RDF

Eight variants of experimental RDF were made based on the results of studies carried out using methods of thermal and thermogravimetric analysis of MSW components and data on the average morphological composition of combustible solid waste, which can be a raw material for RDF (**Fig. 3.3**). RDF samples were made by mixing the components in the required ratio (**Table 3.4**).

According to the research results, data on the change in temperature (T) and mass of the sample (TG), rate of mass change (DTG) and heat generation (DTA) were obtained during the heating process. Processing and analysis of the obtained data made it possible to determine the temperature ranges of dehydration, thermal decomposition of organic and mineral substances, moisture and ash content of the samples (**Table 3.5**).

Temperature ranges, proportions and average rates of decomposition of organic substances of the fuel were calculated (**Table 3.6**). The analysis of the obtained data makes it possible to estimate the kinetics of thermal destruction of organic substances.

Table 3.4 RDF composition

RDF sample	**RDF components, %**					
	cardboard	**polyethylene film**	**polyethylene terephthalate (PET) bottle material**	**fabric**	**genuine leather**	**pine wood**
A	50	26	0	16	3.5	4.5
B	37	40	0	15	3.5	4.5
C	36	0	41	15	3.5	4.5
D	25	25	25	16	4	5
E	47	39	0	7	3.5	3.5
F	29	31	0	13	4	23
G	0	50	0	20	10	20
H	50	50	0	0	0	0

Table 3.5 Thermal characteristics of experimental fuel

RDF sample	Water removal		Thermal decomposition				Ash content, % DM
			organic substances		mineral substances		
	range, °C	moisture content, %	range, °C	content, % DM	range, °C	content, % DM	
A	23–166	6.28	166–530	91.32	530–1000	3.81	4.87
B	20–166	4.69	166–538	92.69	538–1000	3.58	3.73
C	20–165	5.31	165–573	93.66	573–1000	2.95	3.39
D	23–164	4.13	164–560	92.73	560–1000	2.37	4.90
E	23–156	4.78	156–536	91.02	536–1000	4.41	4.57
F	20–165	5.17	165–534	92.79	534–1000	3.69	3.52
G	23–154	4.51	154–544	95.92	544–1000	2.19	1.89
H	23–157	3.81	157–534	90.54	534–1000	4.73	4.73

Note: DM – dry matter

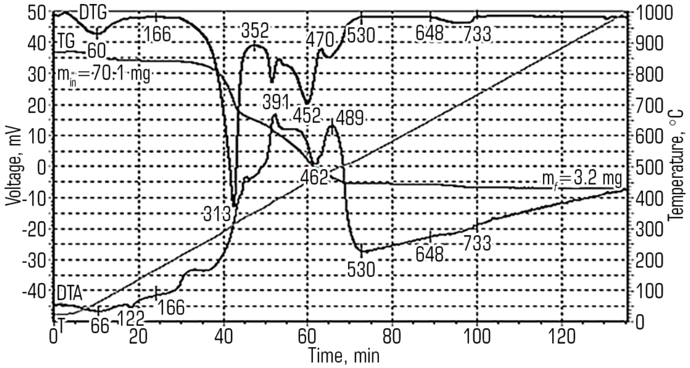
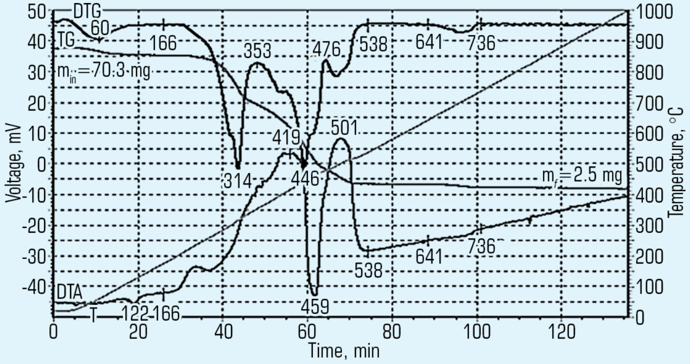
Table 3.6 Temperature ranges, proportions of decomposed organic substances and average rates of RDF decomposition

RDF sample	First stage			Second stage			Third stage			Average rate of decomposition, % DM/min
	range, °C	proportion, % DM	decomposition rate, % DM/min	range, °C	proportion, % DM	decomposition rate, % DM/min	range, °C	proportion, % DM	decomposition rate, % DM/min	
A	166–352	43.99	1.87	352–470	38.05	2.41	470–530	9.28	0.96	1.86
B	166–353	35.67	1.52	353–476	46.27	2.87	476–538	10.75	1.06	1.86
C	165–351	31.56	1.30	351–457	41.45	3.06	457–573	20.65	1.22	1.71
D	164–351	27.45	1.12	351–455	45.25	3.54	455–560	20.03	1.27	1.75
E	156–355	36.99	1.48	355–477	44.44	2.78	477–536	9.59	0.98	1.79
F	165–357	41.47	1.71	357–463	37.61	2.72	463–534	13.71	1.22	1.88
G	154–336	30.13	1.29	336–487	56.33	2.89	487–544	9.46	1.0	1.84
H	157–361	35.73	1.39	361–472	42.44	2.90	472–534	12.37	1.21	1.79

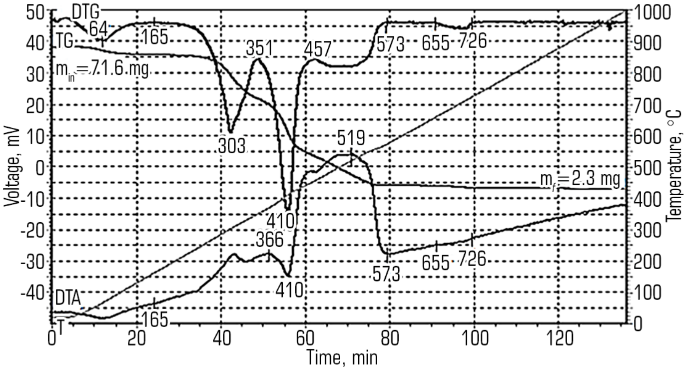
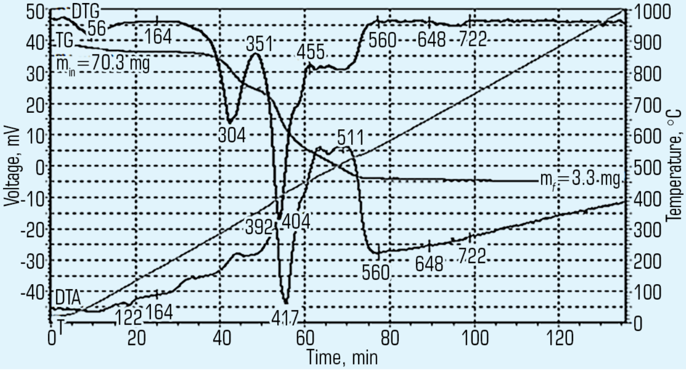
The resulting derivatograms of thermal decomposition of RDF samples and their description are presented in **Table 3.7**. Derivatograms show T, TG, DTG and DTA profiles during sample heating. All samples are characterized by a three-stage destruction accompanied by endothermic and exothermic effects. Dehydration takes place at the first stage, thermal decomposition of organic substances at the second stage, and decomposition of mineral substances at the third stage (**Table 3.5**).

The calorific value was determined according to the standard technique for solid fuels [28–30].

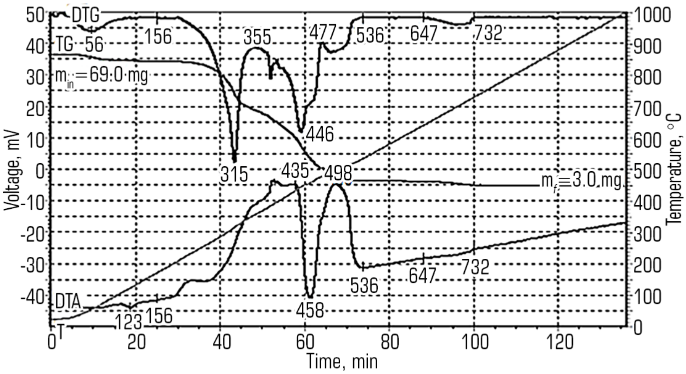
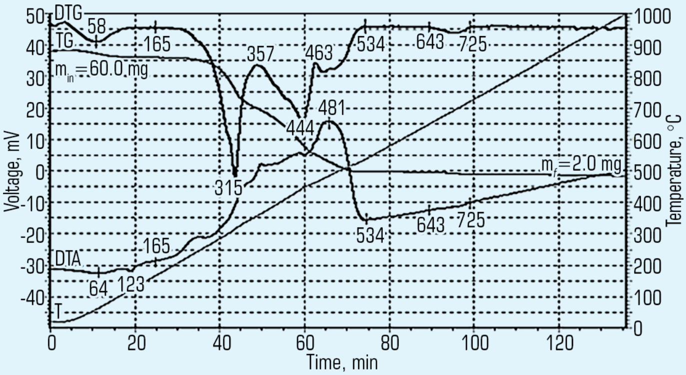
Table 3.7 Derivatograms of thermal decomposition of RDF samples and their description

RDF A	
RDF A description	Dehydration occurs in the range of 23–166 °C. The moisture content of the sample is the highest among all fuel samples due to the high content of cardboard. The thermal decomposition of organic substances occurs in three stages differing in the decomposition rate and thermal effects. Decomposition of 43.99 % DM occurs in the range of 166–352 °C at a rate of 1.87 % DM/min (**Table 3.6**). At the same time, heat generation is constantly increasing. At this stage, the maximum decomposition rate was registered at a temperature of 313 °C. The decomposition rate increases to 2.41 % DM/min in the second stage (352–470 °C) due to polyethylene. The intense emission of gases outside the crucible leads to heat loss, which is registered on the DTA curve in the form of an endothermic peak with a maximum at 463 °C. The decomposition of organic substances is completed at the third stage in the range of 470–530 °C. A further increase in temperature causes the decomposition of mineral substances. Sample mass loss (TG and DTG curves) and heat absorption (DTA curve) are observed at temperatures of 648–733 °C. This is a consequence of the thermal dissociation of calcium carbonate in the cardboard. The ash content of RDF A is 4.87 % DM, and the determined net calorific value is 23.03 MJ/kg
RDF B	
RDF B description	Dehydration of RDF B ends at 166 °C, as for RDF A, after which the stage of decomposition of organic substances begins (**Table 3.5**). This stage is also characterized by three stages of decomposition (**Table 3.6**). At the first stage (166–353 °C), 35.67 % DM is removed at a rate of 1.52 % DM/min. At the second stage (353–476 °C), the intensity of decomposition increases 1.9 times due to the high content of polyethylene film in the fuel. In the range of 419–501 °C, a strong endothermic peak

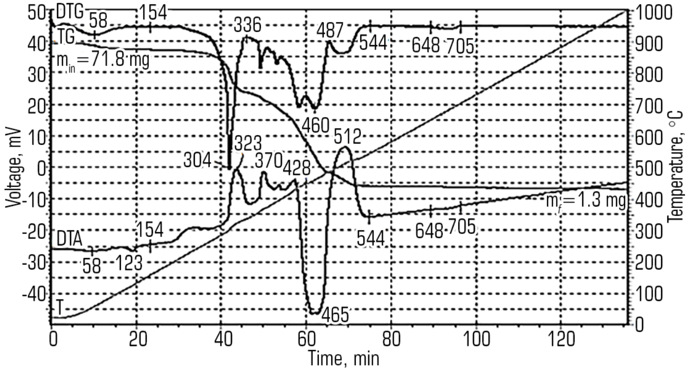
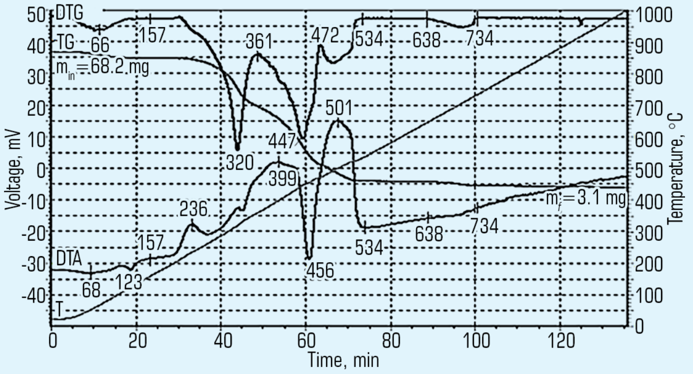
Continuation of Table 3.7

	is registered on the DTA curve, which was observed during the decomposition of the polyethylene sample. At the third stage (476–538 °C), the intensity of decomposition of organic substances decreases. Increasing the polyethylene film content and decreasing the cardboard content in RDF B causes changes in the nature of the destruction of organic substances. The impact of polyethylene as a fuel component becomes more noticeable and causes a powerful release of decomposition products. At the same time, the net calorific value of RDF B increases to 27.01 MJ/kg compared to RDF A due to the contribution of the net calorific value of polyethylene film (42.56 MJ/kg)
RDF C	
RDF C description	The thermal decomposition of RDF C, in which PET bottle material was added instead of polyethylene film, is generally similar to RDF B. Water is removed in the range of 20–165 °C (**Table 3.5**). A slight increase in heat release is observed (DTA curve) at the first stage of decomposition of organic substances (165–351 °C). At the second stage, intense destruction is observed – the rate of decomposition increases by 2.4 times (**Table 3.6**) and reaches a maximum at 410 °C. Against the background of general heat generation, a small endothermic peak indicates a slight release of gaseous decomposition products outside the crucible. In the range of 457–573 °C (third stage), the rate of decomposition decreases and completely stops when reaching 573 °C (DTG and DTA curves). Thermal dissociation of calcium carbonate in cardboard is registered in the range 655–726 °C (DTG and DTA curves). The calorific value of fuel is reduced to 18.85 MJ/kg due to the replacement of polyethylene film with material from a PET bottle in the composition of RDF C
RDF D	

Continuation of Table 3.7

RDF D description	The thermal decomposition of the RDF D occurs according to the decomposition patterns of RDF C. The moisture content of RDF D is 4.13 % due to the low content of cardboard (**Table 3.5**). The stages of decomposition of organic substances differ significantly in decomposition rates (**Table 3.6**). A high content of polymer materials (50 %) causes an increase in the rate of decomposition in the second stage (351–455 °C) and the formation of a significant amount of gaseous products. These products escape the sample and cause a large heat loss, reflected as an endothermic peak in the DTA curve appears as an endothermic peak on the DTA curve with a maximum at 417 °C. The destruction of organic substances ends at 560 °C and is accompanied by a decrease in heat generation. The calorific value of this fuel is 24.60 MJ/kg
RDF E	
RDF E description	Water removal ends earlier by 8–10 °C compared to previous fuel samples (**Table 3.5**). The decomposition of organic substances occurs in three stages, as for all experimental fuel samples. The highest intensity is characteristic of the second stage due to the high content of polymer components. Decomposition of 44.44 % DM occurs at a rate of 2.78 % DM/min. In the range of 435–498 °C, an endothermic peak is registered on the DTA curve with a maximum at 458 °C. It is a consequence of heat loss due to the formation of a significant amount of gaseous products leaving the sample location. The destruction of organic substances ends at 536 °C. The net calorific value of the fuel is 26.46 MJ/kg due to the high content of polyethylene film
RDF F	

Continuation of Table 3.7

RDF F description	Water is removed from RDF F in the temperature range of 20–165 °C, after which the organic substances of RDF fuel decompose in three stages (**Table 3.5**). In the first and third stages, a slightly lower rate of decomposition is observed than in the second (**Table 3.6**), which is a consequence of deeper destruction processes in the second stage and the influence of the kinetics of polyethylene film decomposition. Heat generation increases in the second stage and reaches its maximum at 481 °C (DTA curve). In this case, the endothermic peak accompanying the formation of gaseous substances is not observed. Thermally unstable mineral substances degrade in fuel components in the range of 534–1000 °C with the formation of simpler molecules. The ash content is determined to be 3.52 % DM. The process of calcium carbonate dissociation was observed in the range of 643–725 °C. The net calorific value of this fuel composition is 25.22 MJ/kg
RDF G	
RDF G description	Water removal occurs in the narrowest range of all samples (23–154 °C) due to the absence of cardboard in the composition. The decomposition of organic substances is accompanied by intense gas formation, as evidenced by three endothermic peaks (323–370, 370–428, 428–512 °C) of different intensity. Most organic substances is removed at a rate of 2.89 % DM/min in the second stage of decomposition. The lowest content of mineral substances (2.19 % DM) and ash content (1.89 % DM) is observed in RDF G among all experimental fuel samples due to the absence of cardboard in the fuel composition. The selected fuel composition provided the highest calorific value – 30.82 MJ/kg
RDF H	

Continuation of Table 3.7

RDF H description	RDF H contains cardboard and polyethylene film in equal proportions and has the lowest moisture content (3.81 %). The destruction of organic substances occurs according to the patterns characteristic of the above fuel samples, in particular RDF B and RDF E. The net calorific value of the fuel sample is 28.89 MJ/kg

The analysis of the obtained data makes it possible to compare the destructive processes occurring in the fuel when it is heated to 1000 °C. Dehydration of all RDF samples is completed at a temperature of 154–166 °C (**Table 3.5**). The lowest temperature of the dehydration completion (154 °C) is found in the RDF G sample, which does not contain cardboard. RDF A has a narrower range of decomposition of organic compounds (364 K). This is explained by the presence of a significant amount of cardboard in the composition, the decomposition of which is completed earlier by 23 K than polyethylene and by 79 K than PET. The widest range (408 K) is registered in RDF C, which has the highest PET content. The highest values of the average rate of decomposition have RDF A, B and F, which do not contain PET. It follows from this that an increase in the PET content in fuel causes an expansion of the temperature range of decomposition and a decrease in the overall rate of the decomposition of organic substances.

DTA profiles (**Table 3.7**) indicate that for RDF containing only polyethylene polymers (**Table 3.5**), the release of gaseous substances occurs with an endothermic peak located in the range of 456–465 °C. The same behavior and a similar maximum of the endothermic peak (459 °C) were observed during the decomposition of polyethylene film. The PET presence in the fuel accelerates the release of gaseous substances. The maximum of the endothermic peak is registered at 410 °C (RDF C) and 417 °C (RDF D). In PET, this maximum was registered at 418 °C.

Determination of the calorific value Q_n^d of experimental fuel compositions showed (**Fig. 3.13**) that the highest calorific value is for RDF G, which does not contain cardboard, and the lowest is for RDF C, which does not contain polyethylene film.

Conditional thermal effects (CTE) of thermal decomposition of organic substances were also determined using the "Derivatograph" application program (**Fig. 3.13**). CTE was calculated as the area between the DTA curve and the most likely estimated DTA baseline divided by the mass of the organic substances of the sample. The baseline is a straight line connecting the points of complete dehydration and completion of heat release. The area under the curves of exothermic thermal effects was determined by the trapezoidal method using the "Derivatograph" program.

According to the obtained data, RDF E has the highest value of the specific thermal effect, and RDF D has the lowest value. As it is possible to see, this does not correspond to the results for determining the lower calorific value (**Fig. 3.13**). This confirms the assumption that the registered endothermic peak (DTA curves) underestimates the CTE value due to the loss of heat of thermal decomposition due to the emission of gaseous substances outside the crucible. Therefore, more accurate research results, namely a determined net calorific value of samples, should be taken into account when assessing the thermal characteristics of multicomponent RDF.

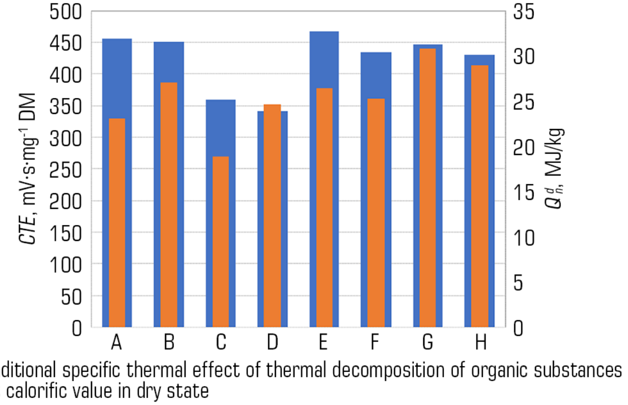


Fig. 3.13 Conditional thermal effects (CTE) and net calorific value Q_n^d of RDF samples

Thermal analysis of experimental RDF based on combustible components of the MSW showed that the temperature of the drying agent should be such as to prevent overheating of the material above the temperature of its complete dehydration during convective drying. This measure will prevent ignition of RDF in the dryer.

The following conclusions can be drawn from the results of experimental studies:

1. The thermal decomposition of RDF was investigated using thermal analysis methods in the range of 20–1000 °C. Temperatures characterizing different stages of destruction, moisture and ash content of samples, rate of thermal decomposition of organic substances, conditional thermal effect and calorific value were determined.

2. It was established that the high polyethylene content in RDF leads not only to a high calorific value of the fuel, but also to a powerful release of volatile thermal decomposition products. This improves combustion kinetics. Polyethylene terephthalate also intensively emits gaseous products during thermal decomposition. However, increasing the polyethylene terephthalate content reduces the calorific value of the fuel due to its significantly lower calorific value compared to polyethylene. Therefore, it is better to send PET products to recycling as much as possible at the stage of waste sorting.

3. Destruction of cardboard does not cause emissions of harmful compounds. However, it should be taken into account that a high content of cardboard causes an increased ash content of the fuel. It was established that the ash content can vary in the range of 1.8–16 % DM for different samples of paper and cardboard. In addition, it is necessary to take into account the presence of chalk in them. Because the decomposition of chalk requires additional energy at sufficiently high temperatures.

Based on the obtained data, it is possible to recommend the presented compositions RDF A and F, which satisfy the conditions set for fuel, as well as RDF B, D and E while ensuring the neutralization of harmful emissions.

CONCLUSIONS

1. Analysis of technological stages of RDF production shows that all stages of production are energy consuming. The consumption is especially large for drying processes. They account for about 40–50 % of total energy consumption. The consumption increases up to 70 % in cases of drying MSW with high moisture content.

Increasing the calorific value of composite fuel based on MSW requires combining components whose thermal properties have not been sufficiently studied. RDF combustion also requires knowledge of the kinetics of thermal decomposition and heat generation.

2. The kinetics of convective drying of RDF of different compositions was studied depending on the temperature (80–120 °C) and the rate of the heat carrier (1.5–2.5 m/s). The drying time is reduced by 56 %, and the maximum drying rate increases by 1.82 times when the heat carrier temperature increases from 80 to 120 °C. Increasing the rate of the heat carrier from 1.5 to 2.5 m/s reduces the drying time by 38 % at a temperature of the heat carrier of 120 °C. The drying time increases by 28 % when the RDF composition changes from the content of polymer materials (31–50 %) to the content of paper and cardboard (31–50 %).

3. The study of heat and mass transfer during drying of fuels, in particular the temperature coefficient, Rebinder number and heat flow, depending on the moisture content of fuels at constant temperatures, showed the feasibility of drying at higher temperatures.

4. RDF was studied in the range of 20–1000 °C using thermogravimetry and differential thermal analysis methods. It is shown that the thermal decomposition of organic substances is staged in RDF. The stages differ in both temperature ranges and decomposition rates.

5. Based on the obtained data, it is possible to recommend the compositions RDF A and F, which satisfy the conditions set for fuel, as well as RDF B, D and E while ensuring the neutralization of harmful emissions.

6. It would be rational to have the maximum amount of polymers, especially polyethylene, in the fuel based on the calorific value and kinetics of thermal decomposition of experimental RDF. However, in practice, the polymer content in the fuel will be determined by the air emission treatment system of a particular energy enterprise.

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