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Research of the Energy Characteristics of Municipal Solid Waste in Cherkassy

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Abstract. The waste management system of Ukraine, is being reformed to bring it in line with European standards for the use of the material and energy potential of waste. Selection of the optimal system should be based on the statistical representativeness of the results of a detailed analysis of the morphology of the municipal waste of each locality in accordance with the socio-economic profile of individual zones of the city and the seasons of the year, as well as the energy and environmental characteristics of the waste. But there are no standards for determining of energy characteristics of municipal solid waste in the country. This paper shows results of characteristics research of municipal solid waste in Cherkassy city carried out in accordance with the new approaches. A methodology for determining the humidity, net calorific value and ash content of municipal solid waste is developed. The results of experimental studies of humidity, calorific value and ash content for 8 components of waste: paper, cardboard, composite materials, textiles, hygiene products, plastic, other combustible materials, wood shavings are presented. Humidity is also determined in organic residues and in fine fractions. The results of the research are used to develop an integrated waste management and recycling system in Cherkassy.

Keywords: morphological composition, secondary energy resource, municipal solid waste, methodology, calorific value, moisture, ash content.

1 Introduction

The increase in the amount of waste is a concern for many countries in the world. Accumulation of municipal solid waste (MSW) threatens to become a global problem for Ukraine. For many years the country has been working on a simplified system of solid waste management, when almost all waste was mixed in a general not weatherproof container and was taken for disposal in landfills.

In the context of the global trend to reduce the consumption of fossil fuels and replacing them with renewable and alternative sources of energy legislation of the civilized countries of the world is directed at the use of material and energy potential of MSW (more than 20 % of the municipal solid waste of these countries is used for the production of electric and thermal energy) [1]. This approach is enshrined in the Framework Directive No 2008/98/EU of 19.11.2008 “On waste and repealing certain Directives”, also known as the Waste Framework Directive or WFD [2], etc.

European principles of waste management laid the basis for a National waste management strategy (NWMS) in Ukraine till 2030, approved by the Cabinet of Ministers of Ukraine [3]. Within two years after the approval of the NWMS, regional waste management plans should be developed. Selection of the waste management system should be based on the analysis of MSW morphology of and energy characteristics of its components.

For the implementation of the principles of NWMS Cherkassy city Council supported by the Ministry of Finance of France, invited the French company “BETEN INGENIERIE” to develop Ukraine’s first integrated project for the disposal, processing, valorization (increasing the cost by selecting components for reuse) and efficient secondary recycling of solid waste in Ukraine. The purpose of the project is to optimize and substantiate the processes of municipal solid waste management, reduce the amount and area of landfills in the city of Cherkasy and the surrounding area, and build waste composting and sorting plant.

The company “BETEN INGENIERIE” has analyzed the morphology of MSW to study their exact annual composition in accordance with the demographic and socio-economic profile of individual areas of the Cherkassy city (population, trade establishments, industrial facilities), in accordance with the accepted European methodology.

Analysis of the energy characteristics of MSW components in Cherkassy city, which can be used for energy valorization, and nutrient content in the waste that is subject to composting, was performed by the Institute of Technical Thermophysics of the National Academy of Sciences of Ukraine on request and with the financing of "BETEN INGENIERIE".

2 Literature Review

The main energy characteristics that determine the expediency of using MSW as a secondary energy resource are humidity, net calorific value (NCV) and ash content.

The research of these characteristics is carried out by experts from many countries of the world. Analysis of publications carried out by the authors [4], showed significant difference in the classification of the morphology of solid waste and in calorific value of components in different countries and Ukraine (Table 1). According to the Commission's Decision on the European List of Waste [5], the classification of MSW components includes 40 items, while in Ukraine, according to the Order Ministry of Regional Development, Construction and Housing and Communal Services of Ukraine of Ukraine, only 11 ones [6], which complicates the study of component characteristics.

Table 1 shows that the use of MSW as a secondary energy source can replace the corresponding amount of fossil fuels, which is extremely relevant for Ukraine [7].

Table 1 – Generalized morphology and net calorific value of MSW components in the leading countries of the world, Ukraine and CIS countries

The type of MSW component	Net calorific value of solid waste, MJ/kg			
	EU, WB	Ukraine (data up to 2014)	Russian Federation	Kazakhstan
Organic materials (Food waste)	1.9–4.1	3.1–3.8	3.4–6.2	3.3
Paper and cardboard	6.5–16.0	7.5–11.5	9.5–15.0	9.9
Plastic	20.1–35.0	24.4	24.4–28.0	24.4
Textiles	11.8–19.0	12.1–15.0	14.0–19.1	15.7
Leather and rubber	N/A	20.9–25.2	23.0–33.5	25.8
Wood	13.6	13.4–14.5	14.0–15.0	14.5
Small remains	2.6–3.5	3.1	4.6–8.7	4.6
Other	32.0	N/A	18.1	N/A

This work is aimed at the adaptation of the MODECOM methodology for the determination of the morphological composition of MSW with taking Ukrainian conditions into account; development of recommendations for methodological approaches to the determination of energy characteristics of MSW components in Ukraine: humidity, NCV and ash content, as well as conducting experimental studies of the energy characteristics of Cherkassy city.

3 Research Methodology

3.1 Methodology of determination of morphological composition

The MODECOM methodology is developed by the French Agency for Environmental Management and Energy Management (ADEME) and fully complies with European standards aimed at ensuring the statistical representativeness of the research results. In particular, samples are collected in different areas of the city in accordance with the demographic and socio-economic profile of individual zones. In addition, samples are taken from both housing stock and commercial, administrative and industrial facilities. Typically, samples are taken from (1) the private sector, (2) the sector of multiapartment buildings, (3) the trade and administrative sector, (4) the industrial zone.

The morphological composition of MSW was determined by the following indicators:

– granulometry;
– type of material;
– potential to avoid landfill.

Morphological study complied the requirements of European regulations - on sampling waste (standard EN 14899) and on the collection of samples of solid waste in containers (norm X30-413).

In Cherkassy, 13 samples weighing around 600 kg were selected in each of the two worst seasons of the year (due to the high humidity of the solid waste): December-January and August-September, which ensured high accuracy of the results.

For sorting by category, each sample was mixed, then sorting was done according to the size of the waste (more than 100 mm, from 20 to 100 mm, up to 20 mm), the type of material (13 categories: organic, paper, cardboard, composite materials, textiles, sanitary textiles, plastics, combustible materials, glass, metals, non-combustible materials, hazardous household waste, fine fraction (up to 20 mm), and subspecies of material (more than 30 subcategories). Further systematic weighing of samples of waste was carried out.

3.2 Methodology of determination of MSW energy characteristics

At present, Ukraine has no standards for the study of humidity, NCV and ash content for MSW, but standards exist for defining these characteristics for solid organic fuels [8–11]. At the same time, international standards and harmonized standards exist in some CIS countries [12–15]. These standards have some differences in methods of preparation of samples, measurement and processing of their results. Most studies have been carried out in accordance with Ukrainian standards, but, taking into account the peculiar properties of MSW, certain operations have been conducted with taking into account requirements of international standards.

The main difference between solid waste and conventional solid organic fuels, in terms of experimental determination of energy properties, is its significant heterogeneity, both in composition and in humidity.

In the study of fuels, as a rule, an analytical sample of 1 g is prepared, shredding it to the size of the particle of 0.1–0.2 mm and homogenizing.

Analysis of the energy characteristics of MSW components in Cherkasy city was conducted for 11 separate components, exceeding the classification according to the Order of the MHCP of Ukraine [6]. All materials that were not included in the inert and reprocessed waste were analyzed. The preparation of experimental samples showed a significant heterogeneity of the components of the MSW even within one component, which, due to the small weight and the need for thorough homogenization of the sample significantly complicated the study of characteristics and resulted in a significant dispersion of results and increase uncertainty of measurements. This is confirmed by previous authors' studies [4].

The analytical sample is kept in the laboratory room until the air-dry state is reached, and then at least two parallel measurements of the moisture, ash content and NCV of the analytical sample were carried out. The difference in measurement results in parallel measurements should not exceed the limits specified with the normative documents. The moisture for each component was measured at the delivery state for the entire sample volume, then the components were shredded, homogenized, dried and brought to air-dry state, the humidity and ash content in the analytical state were measured for the entire volume of the prepared specimens.

In the NCV study of heterogeneous samples, a spread of measurement results was observed that exceeded the permissible difference between the two measurements, so at least five experiments were performed and the result was defined as arithmetic mean. For a qualitative study of the energy characteristics of MSW, it is appropriate for Ukraine to introduce a more detailed European classification.

3.3 Method of determination of moisture content

For each of the components provided, the determination of relative humidity is made for two states - delivery and analytical. The method consists in weighing the sample in the initial state, drying the sample at a given temperature to a constant mass and weighing the sample in a dry state. Drying of most samples is carried out at temperature (105 ± 2) °C, but for components with low melting temperature, for example, polyethylene or Styrofoam, drying is carried out at a temperature (70 ± 2) °C. Relative humidity was determined by the ratio of the total change in mass of the sample to the initial mass.

3.4 Method of determination of ash content

The ash content of samples were determined by the slow ashing in accordance with the requirements of GOST 11022-95 (ISO 1171-97) [9]. A crucible or a boat with the sample is weighed and placed in muffle, heated to 500°C for 60 minutes and held at this temperature for 60 minutes, then the temperature was raised to (815±10)°C for 60 minutes and maintained at this kept for 2 hours. Different duration of exposure is recommended for different types of traditional fuels, usually from 30 minutes to 2 hours, for a MSW test the maximum duration of 2 hours were selected. After exposure crucible or boat is taken out of the oven, cooled for 5 minutes on a ceramic or metal support and then in a closed desiccator to room temperature and weighed. The ash content of the analytical sample was calculated as a percentage that represents the ration between weights of the remnants after ashing and the initial mass of sample.

3.5 Method of determination of net calorific value

The methodology generally complies with the standard methods for solid fuels GOST 147-95 (ISO 1928-76) [10] and DSTU ISO 1928 [11].

Measurements were carried out in an automated bomb calorimeter of the heat flow (Kalve type) [16]. The device is anhydrous, does not require water weighing and a determination of its temperature rise, as required by traditional water calorimeters. After completion of measurements, the device outputs the energy Q_T (J) allocated in the bomb.

Net calorific value of combustion of an analytical sample in a bomb is Q_b^a calculated by the formula, kJ/kg:

$$Q_b^a = \frac{Q_T - q_{\rm wr} \cdot (m_1 - m_2) - q_{pap} \cdot m_4}{m_3}, \qquad (1)$$

where Q_T is the total heat emitted during the combustion of the sample according to the readings of the device; q_{wr} = 2 510 kJ/kg, q_{pap} = 15 627 kJ/kg – specific calorific value of inflammable wire and paper package; m_1, m_2 – initial and remaining mass of the wire; m_3 – mass of sample; m_4 – mass of the paper package.

Gross calorific value of an analytical sample, taking into account corrections for the creation and dissolution of acids, was calculated according to [10, 11] by the formula, kJ/kg:

$$Q_s^a = Q_b^a - \left(94 \cdot S^a + \alpha \cdot Q_b^a\right), \qquad (2)$$

where 94 – coefficient, taking into account the heat of formation of sulfuric acid from sulfur dioxide and dissolution of sulfuric acid in water by 1 % sulfur, passed at combustion of fuel in sulfuric acid, kJ/kg; S^a – mass fraction of sulfur in the analytical sample of fuel, %; $\alpha \cdot Q_b^a$ – an amendment that takes into account the heat of formation and dissolution in water of nitric acid, the value of which is determined by calibrating the calorimeter $\alpha \cdot Q_b^a = 29$ kJ/kg.

The higher heat of combustion for dry fuel at constant volume Q_s^d and fuel in the delivery condition was calculated according to the formulas, kJ/kg:

$$Q_s^d = Q_s^a \frac{100}{100 - W^a}; \quad Q_s^r = Q_s^a \frac{100 - W^r}{100 - W^a}. \qquad (3)$$

In determining of the net calorific value according to the standards [10, 11], generally use the notion of NCV at constant volume, which is traditionally calculated by the formulas, kJ/kg:

– for working condition:

$$Q_i^r = Q_s^r - 24{,}42\left(W^r + 8{,}94 H^r\right); \qquad (4)$$

– for dry condition:

$$Q_i^d = Q_s^d - 24{,}42 \cdot 8{,}94 H^d = Q_s^d - 218{,}3 H^d. \qquad (5)$$

The Annexes to these standards also provide formulas for calculating the calorific value at constant volumes, which are harmonized with the current international standards, and have different calculation factors, kJ/kg:

– for working condition:

$$Q_{i,V}^r = \left(Q_{s,V}^d - 206 H^d\right)\frac{100 - W_t^r}{100} - W_t^r; \qquad (6)$$

– for dry condition:

$$Q_{i,V}^d = Q_{s,V}^d - 206 H^d. \qquad (7)$$

In the latest standards [12–15], on the contrary, the concept of calorific value at constant pressure is the main one and the following formulas are given, kJ/kg:

– for working condition:

$$Q_{i,p}^W = [Q_{s,V}^d - 212{,}2 H^d - 0{,}8(O^d + N^d)] \times \times \left(1 - 0{,}01W\right) - 24{,}43W; \qquad (8)$$

– for dry condition:

$$Q_{i,p}^d = Q_{s,V}^d - 212{,}2 H^d - 0{,}8\left(O^d + N^d\right) \qquad (9)$$

The analysis of the above formulas shows that the difference in the results of the calculations by the various given methods is rather small, but for the verification of this fact, parallel calculations for the dry fuel state according to formulas (5), (7), (9) have been performed and the relative (in percentages) the difference between the largest and the smallest values (Table 2).

For arbitrary working humidity W^r and ash content A^r, hydrogen and sulfur content is calculated according to the formulas [17], %:

$$\mathrm{H^r} = \mathrm{H^{daf}} \times \frac{100 - W^r - A^r}{100}; \quad \mathrm{S^r} = \mathrm{S^{daf}} \times \frac{100 - W^r - A^r}{100}. \qquad (10)$$

In the above formulas, *A* is ash content; *W* – humidity; *H*, *N*, *O*, *S* – relative content (as a percentage) of hydrogen, nitrogen, oxygen, sulfur, respectively; upper indexes of the designation of the state: *d* - dry, daf – dry, ash free, *r* – working (deliveries); lower indices: *s* – gross heat; *i* – net heat; *p* – under constant pressure; *V* – for constant volume.

4 Results

Calculations of NCV were done for the three conditions of components: analytical Q_i^a, delivery Q_i^r, dry Q_i^d. The results of calculations are presented in Table 2. The table also shows the values of NCV at constant volume $Q_{i,V}^d$ and at constant pressure $Q_{i,p}^d$, calculated from formulas (7) and (9), and the highest relative (in percent) difference between values for dry state.

According to the calculations, it was found that the difference between the values of the heat of combustion for the dry state, calculated according to different methods, does not exceed 0.54 %, and the absolute difference is less than 0.12 MJ/kg, that does not exceed the value of the permissible difference of the results in the measurements . Thus, for technical calculations, the use of each of the values is permissible, and then the value Q_i^d calculated by formula (5) is given.

Influence of humidity of components on the heat of their combustion is shown in Fig. 1.

The data in Fig. 1 clearly demonstrate the negative effects of moisture on the energy characteristic of solid waste.

The following parameters were studied:

– calorific value and the content of heavy metals in waste;

– the content of nutrients in the waste that is subject to composting;

– the content of heavy metals in MSW that is to be buried.

The main results of determining the humidity, calorific value and ash content of MSW components in Cherkassy city is given in Table 3.

Table 2 – Results of NCV determination for MSW components by different methods

Generic component name	H^{daf}, %	Q_i^a, MJ/kg	Q_i^r, MJ/kg	Q_i^d, MJ/kg	$Q_{i,V}^d$, MJ/kg	$Q_{i,p}^d$, MJ/kg	max δQ_i^d, %
Paper	6.2	13,236	9.335	14.334	14.410	14.372	0.53
Cardboard	6.2	13.221	8.407	14.195	14.271	14.232	0.54
Composite materials	7.2	27.639	20.450	28.542	28.631	28.586	0.31
Textiles	6.8	15.784	10.481	16.789	16.873	16.830	0.50
Hygiene products	6.8	25.944	2.617	27.314	27.398	27.356	0.31
Plastic	9.3	38.020	33.164	38.355	38.469	38.412	0.30
Other flammable materials	7.2	17.872	16.166	18.186	18.274	18.230	0.49
Wood parcel (Green waste)	6.1	16.721	15.952	18.166	18.241	18.203	0.41

Table 3 – The main results of determining the humidity, ash content, calorific value of MSW components in Cherkassy city

Generic component name	Delivery condition (working condition)				Dry condition, W = 0 %		
	Humidity Wr, %	Ash content Ar, %	GCV Q_s^r MJ/kg	NCV Q_i^r MJ/kg	Ash content Ad, %	GCV Q_s^d MJ/kg	NCV Q_i^d MJ/kg
Paper	30.2	7.8	10.95	9.33	11.2	15.69	14.33
Cardboard	35.1	8.3	10.09	8.41	12.8	15.55	14.19
Composite materials	26.4	6.2	22.17	20.45	8.5	30.11	28.54
Textiles	33.3	1.3	12.18	10.48	2.0	18.27	16.79
Sanitary textiles	83.2	1.9	4.83	2.62	11.3	28.80	27.31
Plastic	13.0	4.1	35.13	33.16	4.7	40.39	38.35
Other flammable materials	10.2	10.7	17.74	16.17	11.9	19.76	18.19
Wood parcel (Green waste)	11.1	2.5	17.34	15.95	2.8	19.50	18.17
Organic Remnants	74.9	–	–	–	–	–	–
Small fraction of MSW	47.6	–	–	–	–	–	–

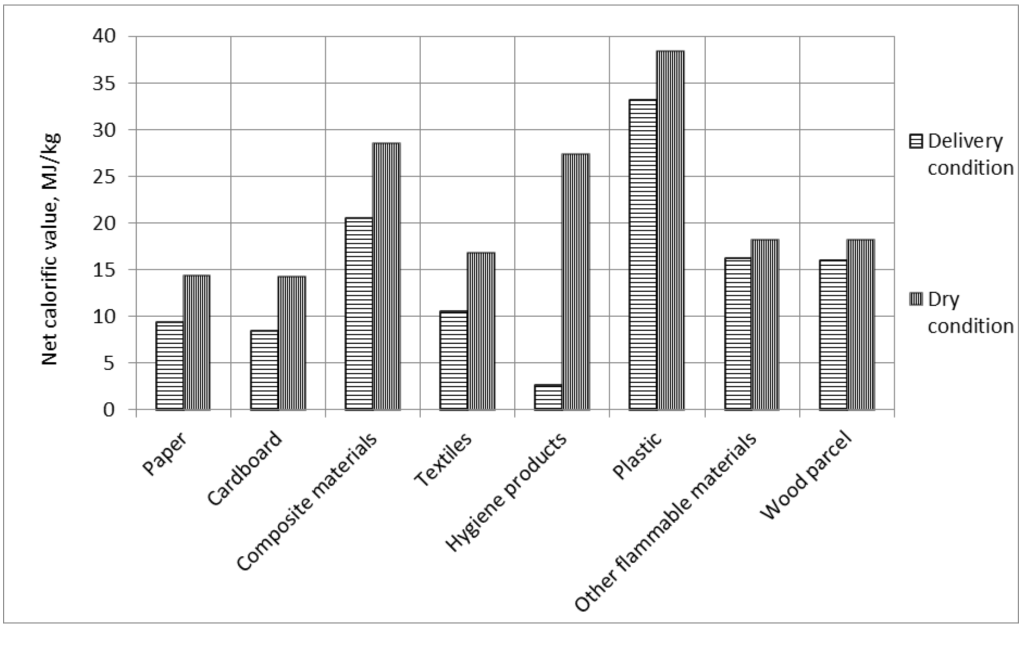

Figure 1 – Influence of humidity on the NCV of MSW components

The results of the research indicate significant differences in the studied characteristics in different components of the waste. The highest content of moisture was attributed to organic residues and hygiene products – 74.9–83.2 %, the smallest – to other combustible materials, wood particles and plastic – 10.2–13.0 %. Hygiene products had the lowest calorific value – 2.62 MJ/kg, the highest – plastic – 33 MJ/kg.

The results of the experimental study of GCV and calculations of the NCV of MSW components in the dry state show a significant increase in calorific value compared to moist components in the delivery state. The calorific value of hygiene products has increased by almost 10 times. The calorific value of the cardboard has increased by 69 %, textiles – by 60 %, paper – by 54 %, composite materials – by 40 %. The calorific value of components with less hygroscopicity has increased significantly less: calorie plastic increased by 16 %, other combustible materials – by 12 %, wood particles – by 14 %.

The results of ash content studies of MSW components in the delivery state showed values ranging from 1.3 % (textiles) to 10.7 % (other combustible materials). The ash content of MSW components in the dry state ranged from 2.0 % (textiles) to 12.8 % (cardboard).

The values of ash content were somewhat higher than that inherent in pure materials, which is probably due to the contamination of the studied components with soil particles.

5 Conclusions

The above described method and process of sorting and weighing of detailed subcategories allows:

– to precisely determine the potential of waste valorization, because today not all types of plastic are valorized with the same way;

– to design, measure, accept and approve the feasibility study for the processing of municipal waste: composting, methanization (biological decomposition with the release of biogas), sorting or use for energy production.

The studies showed significant heterogeneity of MSW components even within the same component that led to substantial variability in results and increase the uncertainty of measurement due to small weight and need for careful homogenization the sample, which experimentally investigated. That significantly complicated the definition of characteristics. This indicates the necessity of adopting in Ukraine of European methods of detailed morphology of solid waste.

The implementation of the NWMS requires the approval of standards for determining the energy performance of municipal solid waste. In the framework of the recommendations on methodological approaches to the definition of moisture content, calorific value and ash content of MSW. Approval of these recommendations was carried out in the study of the energy characteristics of MSW components in Cherkassy city.

The calorific value of MSW depends on the morphological composition and humidity of the components. In the samples tested in the state of supply humidity ranged from 10.2 to 74.9 % with ash content from 1.3 to 10.7 %. Drying of components increases their calorific value from 1.1 to 10.4 times.

It is expedient to optimize the waste collection process in order to efficiently use the energy potential of solid waste. According to European practice, solid waste is collected in closed containers, which are located underground or under sheds, in order to prevent action the atmospheric precipitation on MSW. If possible, such practice should be introduced in Cherkassy city.

The results of the research are used to develop a "Plan to prevent waste generation" and an integrated waste recycling and utilization system in the city of Cherkassy. According to NWMS, such a plan will be mandatory for each city up to 2020.

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Дослідження енергетичних характеристик твердих побутових відходів м. Черкаси

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Анотація. В Україні реформується система поводження з відходами для приведення її у відповідність до європейських стандартів використання матеріального та енергетичного потенціалу відходів. Вибір оптимальної системи має ґрунтуватись на статистичній репрезентативності результатів детального аналізу морфології муніципальних відходів кожного населеного пункту відповідно до соціально-економічного профілю окремих зон міста та сезонів року, а також їх енергетичних та екологічних характеристик. Але в країні відсутні стандарти з визначення основних енергетичних характеристик твердих побутових відходів.Відповідно до нових підходів проведено дослідження твердих побутових відходів м. Черкаси. Розроблені рекомендації щодо методологічних підходів до визначення вологості, теплоти згоряння та зольності твердих побутових відходів. Наведені результати експериментальних досліджень вологості, теплоти згоряння та зольності 8 компонентів відходів: паперу, картону композитних матеріалів, текстилю, продуктів гігієни, пластику, інших горючих матеріалах, деревного оструржку. Вологість визначена також в органічних рештках та у дрібній фракції. Результати дослідження використовуються для розробки комплексної системи переробки та утилізації відходів у м. Черкаси.

Ключові слова: морфологічний склад, вторинний енергоресурс, тверді побутові відходи, методика, теплота згоряння, вологість, зольність.