

**MODEL AND METHOD OF DECISION-MAKING RULES FOR THE FORMATION OF THE STRUCTURE OF TECHNICAL EQUIPMENT IN PROCESSES OF THERMAL DESTRUCTION OF MSW IN THE NORMATION OF ACID GASES EMISSIONS.****O. B. Maksymova<sup>1</sup>, H. P. Lysiuk<sup>2</sup>, K. O. Zhanko<sup>2</sup>, V. P. Bessarab<sup>2</sup>**<sup>1</sup>*Odesa Maritime Academy National University*<sup>2</sup>*Odesa Polytechnic National University*

**Abstract.** A simulation model for the purification process of classified municipal solid waste (MSW) has been developed, taking into account the consumption of resources to bring the resulting carbon-hydrogen gases from the classified MSW of the main group to an environmentally acceptable state, which will ensure that the impurities of groups that form acid gases are taken into account for various conditions of processing by thermal destruction methods. Decision-making rules for the formation of the structure of technical means for the purpose of processing solid waste using thermal destruction. A comprehensive technological scheme of the thermal recycling method is presented, ensuring compliance with environmental conditions for emissions into the environment when using secondary energy resources obtained from solid waste.

**Key words:** municipal solid waste, thermal destruction, thermal utilization, pyrolysis, incineration, acid gases.

**Introduction**

The modern era of the information society is characterized by rapid technological progress, as a result of the fourth and fifth industrial revolutions. The interdisciplinary development of science gives rise to the emergence and introduction of technologies in the shortest possible time in any spheres of industry, energy, and agriculture, which leads to a sharp increase in consumption. This order of things in the modern era and in the near future ensures a significant increase in the volume of industrial waste (IW) and municipal solid waste (MSW). So far, the result of such activities is a significant measure of unpredictable change in the ecosystem and the entire appearance of planet Earth.

At the moment, the management of the education of software and solid waste is the main stage in the stabilization of the ecological component to ensure indicators in the processes of organizational and technical systems and complexes, to increase efficiency, productivity, reliability, rhythm and competitiveness. The minimization of MSW volumes using thermal destruction processes at waste processing facilities has become widely developed in world practice in industrialized countries. Countries such as Denmark, Switzerland and Japan thermally process about 70% of their MSW; Germany, the Netherlands and France - about 40%.

The processes of thermal destruction make it

possible to reduce the mass of waste by 3 times, to eliminate some of its properties: smell, release of toxic liquids, reproduction of bacteria, and also to produce additional energy that can be used for electricity or heating.

Therefore, an important stage of environmental stabilization is the reduction of gaseous emissions during the thermal destruction of solid waste. Technological methods of solid waste preparation for thermal processing and their subsequent minimization by thermal methods, developed in the last decade, make it possible to manage the residual negative impact on the environment when burning the resulting hydrocarbon gases with accompanying acid gases.

**1. Analysis of literary sources**

The work [1] shows that a morphological classification is possible according to the characteristic chemical composition of MSW, which consists of possible chemical elements. The paper [2] shows that despite the diversity of combustible solid waste, the process of formation of combustion products and determination of their temperature can be described using a single model. Let's define a model of the thermal destruction process, which includes atoms [C], [H], [N], [O]. They are typical representatives of solid waste, which cover a wide class of organic waste. Thus, additional consideration of active elements [F], [Cl] and [S] found in MSW and forming acid gases allows to simulate almost all organic compounds that can be isoenthalpically decomposed or burned with a lack or excess of atmospheric air. The basis of the

method is a simulation model, which is represented by a tabular form of gross formulas of possible compounds from which volumes of solid household waste are formed. According to accepted data, 15 compounds were formed in the form of gross formulas.

It is shown in [3] that when burning 1 ton of solid waste at thermal waste processing plants, 4...8 thousand m<sup>3</sup> of flue gases containing nitrogen and sulfur oxides, hydrogen chloride and polyaromatic hydrocarbons, chlorobenzenes and heavy metals are formed.

Light hydrocarbons, polycyclic aromatic hydrocarbons, chlorobenzenes, chlorophenols, polychlorinated dibenzo-p-dioxins and dibenzofurans and dioxin-like polychlorinated biphenyls were studied as solid waste in work [4]. The investigated wastes included: car shredder residues, solid used fuel, tires, sewage sludge, polyvinyl chloride, polychloroprene, various fractions of electrical and electronic waste, cotton and polyester fabrics, meat and bone meal, olive oil waste and various biomass samples. The study included 20 different types of waste.

For the model, the composition of the waste (elemental analysis) and the gas flow rate, which is used as the atmosphere during decomposition, were used as an argument. Hydrocarbon emissions were equated to emissions of one compound (propylene). The simulation allowed the calculation of the percentage of oxygen in the emitted gas, after which the pollutant emissions were converted to standard conditions. In [4], a rule was obtained for PZ between the values of the total estimated amount of gas obtained and the ratio of introduced oxygen.

In [5], pollutant emissions from pyrolysis and combustion of foam plastic at four different temperatures (550°C, 650°C, 750°C and 850°C) were obtained and characterized. Thus, the studies included hydrogen, carbon oxides (CO and CO<sub>2</sub>), nitrous oxide, ammonia, light hydrocarbons, polycyclic aromatic hydrocarbons, chlorinated benzenes, chlorinated phenols, polychlorinated dibenzo-p-dioxins and dioxin-like polychlorinated biphenyls. The pyrolysis experiment at 850°C gives the maximum formation of NH<sub>3</sub>, and the temperature of 650°C is the best condition for the production of large amounts of light hydrocarbons such as methane, ethylene. The authors [5] identified a problem that must be solved when burning foam plastic: there must be localization of NO and HCN emissions. An analysis of gases and semi-volatile compounds was carried out in [5]. According to the results, it was concluded that pyrolytic conditions contribute to the formation of methane, ethylene, NH<sub>3</sub> in the presence of oxygen, which has a high

temperature and heating rate. During the pyrolysis of polyvinyl chloride, an increase in temperature also led to an increase in the formation of methane and ethylene and a decrease in the formation of HCl.

Work [6] reflects the results of pyrolysis and burning of used polyester fabrics. An analysis of the influence of both temperature and the reaction atmosphere on the final products was carried out. More than 160 compounds were identified and quantified, including carbon monoxides, light hydrocarbons, and polycyclic aromatic hydrocarbons. Benzene is the organic compound formed with the highest yield. The levels of polychlorinated dibenzodioxins, polychlorinated dibenzofurans obtained indicate that these wastes can be used alone or possibly with other fuels in energy recovery incinerators.

In literary sources [4,5,6] it is noted that with incineration, the correct conduct of the process is of primary importance, which contributed to complete combustion as much as possible. Maintaining optimal combustion parameters significantly affects the reduction of emissions of organic substances into the atmosphere. A parameter that well characterizes "optimal combustion conditions" is the concentration of carbon monoxide in flue gases. Other parameters that determine "good combustion conditions" are, first of all, temperature, turbulence and residence time of flue gases at the appropriate temperature. Literature sources [1,2,3] state that the sorting of raw materials with given characteristics through identification and classification makes it possible to sequence the sorting of industrial solid waste volumes. The first qualitative sorting is carried out on the basis of identification by the isoenthalpic method, which makes it possible to carry out sorting by the quantitative method on the basis of the express gravimetric method at the second stage. The qualitative method allows, first of all, to sort raw materials, which with a high probability will consist of 80...85% of one type of initial mixture, which significantly reduces the sorting volumes. Traces of compounds that can form acid gases less than 0.1% by mass allow them to be effectively neutralized by special cleaning technologies during direct combustion in industrial boilers. If, as a result of the quantitative method, groups of compounds that can form acid gases are detected, such raw materials can be processed using pyrolysis. In this technology, acid gases entering the synthesis gas are bound on alkaline filters. Most of the compounds in a bound form will remain in the so-called carbonaceous residue. But [3] does not state the decision-making rule for the formation of the structure of technical means for the purpose of solid waste processing. Therefore, the development

of such a rule is an actual topic of research. The relevance is also confirmed by specialized studies analyzed in [4,5,6].

## 2. The purpose and objectives of the research

The purpose of the article is to develop a simulation model of the process of cleaning classified solid waste and decision-making rules for the formation of the structure of technical means for the purpose of processing solid waste by thermal destruction methods while obtaining carbon-hydrogen gases in compliance with environmental indicators.

To achieve the given goal, the following tasks must be solved:

— To develop a simulation model of the cleaning process, which takes into account the cost of resources to bring the obtained carbon-hydrogen gases from the classified solid waste of the main group to an environmentally acceptable state, which will ensure taking into account impurities of groups that form acid gases for various conditions of processing by thermal destruction methods.

— To propose a decision-making rule based on a simulation model of the cleaning process when using different methods of thermal destruction to form the structure of technical means for solid waste processing while complying with environmental indicators

— To develop a complex technological scheme of the method of thermal utilization, which ensures compliance with ecological conditions for emissions to the surrounding natural environment, when using secondary energy resources obtained from solid waste.

## 3. Models and methods

When processing MSW by methods of thermal destruction, the calculation of the lower heat of combustion is calculated according to the model given in [ 7 ]. The first eight equations of the model are represented by the partial pressures of combustion products due to the law of active masses:

$$\frac{P_C \cdot P_O}{P_{CO}} = K_{CO}(T); \quad (1)$$

$$\frac{P_C \cdot P_O^2}{P_{CO_2}} = K_{CO_2}(T); \quad (2)$$

$$\frac{P_H^2 \cdot P_O}{P_{H_2O}} = K_{H_2O}(T); \quad (3)$$

$$\frac{P_H \cdot P_O}{P_{OH}} = K_{OH}(T); \quad (4)$$

$$\frac{P_H^2 \cdot P_O}{P_{H_2}} = K_{H_2}(T); \quad (5)$$

$$\frac{P_O^2 \cdot P_O}{P_{O_2}} = K_{O_2}(T); \quad (6)$$

$$\frac{P_{N_2}^2 \cdot P_O}{P_{N_2}} = K_{N_2}(T); \quad (7)$$

$$\frac{P_N \cdot P_O}{P_{NO}} = K_{NO}(T). \quad (8)$$

The constants of chemical equilibrium are presented in tabular form in the relevant reference books and in the calculations for the corresponding temperature can be selected or calculated using approximation polynomials. In addition, they can be calculated on the basis of enthalpies and entropies of the formation of substances included in the reactions under consideration, which, in turn, are also presented in tabular form, or they can be calculated on the basis of approximation polynomials [8].

The following 4 equations were compiled on the basis of the law of conservation of matter in the form of the equality of the number of atoms of the corresponding chemical element in fuel and combustion products. The number of atoms in the fuel is calculated based on the number of its molecules considered  $M_F$

$$\text{for}[C] \quad b_C \cdot M_F = P_{CO} + P_{CO_2} + P_C; \quad (9)$$

for[H]

$$b_H \cdot M_F = 2 \cdot P_{H_2O} + P_{OH} + 2 \cdot P_{H_2} + P_H; \quad (10)$$

for [O]  $(b_O + \alpha \cdot \chi_0^W \cdot 0.419) \cdot M_F = P_{CO} + 2 \cdot$

$$P_{CO_2} + P_{H_2O} + P_{OH} + 2 \cdot P_{O_2} + P_{NO} + P_O; \quad (11)$$

for [N]  $(b_N + \alpha \cdot \chi_0^W \cdot 1.581) \cdot M_F = 2 \cdot P_{N_2} +$

$$P_{NO} + P_{N-} \quad (12)$$

To close the system, we will use Dalton's law as the basis of the last equation, which expresses the equality of the sum of the partial pressures of the combustion products of the pressure in the furnace of a steam boiler  $P_\Sigma$ :

$$P_\Sigma = P_{CO} + P_{CO_2} + P_{H_2O} + P_{OH} + P_{H_2} + P_{O_2} + P_{N_2} + P_{NO} + P_C + P_H + P_O + P_N. \quad (13)$$

The written model is a system of nonlinear algebraic equations that allows you to calculate the properties during the thermal destruction reaction of solid waste.

Next, consider the calorific value calculation model according to the above model. To do this, we will calculate the molar enthalpies of combustion products  $I_{CP}$  at the reaction temperature and their molar enthalpies of formation under normal conditions  $I_{298}$ . The difference between these two values  $(I_{CP} - I_{298})$  determines the amount of energy in the form of heat released during the formation of one mole of the combustion product, which is considered in the process of burning the original gas mixture. The product  $P_i \cdot (I_{CP} - I_{298})_i$  determines the amount of energy released during the formation of the corresponding combustion product in the combustion process. The sum of these values  $Q_\Sigma = \sum [P_i \cdot (I_{CP} - I_{298})_i]$  gives the total amount of energy released during combustion. The condition

of numerical equality of partial pressures  $P_i$  of combustion products and their molar concentrations is fulfilled for a certain number of moles of fuel  $M_T$ , also determined in the calculation process. Knowing the values  $\sum[P_i \cdot (I_{CP} - I_{298})_i]$  and  $M_F$  allows you to determine the amount of energy  $Q_\mu$  released during the combustion of 1 mole of fuel.

Below is a method of calculating the molar enthalpies of combustion products  $I_{CP}$  at the reaction temperature and their molar enthalpies of formation under normal conditions  $I_{298}$  when using the MSW combustion model. The sequence of actions of the method is based on the assumption that the process of thermal destruction is isoenthalpic. The fuel enthalpy is calculated for the selected MSW-oxidizer pair with known enthalpies  $I^{(MSW)}$  and  $I^{(O)}$  a given value  $\chi^W$  of the molar ratio of the components

$$I^{(F)} = I^{(MSW)} + \chi^W \cdot I^{(O)}. \quad (14)$$

Further, the search for the connection by the model is carried out as follows:

Step 1. The initial temperature approximation is selected  $T^0$ , it is considered to be reached at the current moment during combustion  $T_i = T^0$ .

Step 2. Using the iterative process, the model (5-17) is linearized, the composition (partial pressures  $P_i$  and, as a result, the molar fraction) of the combustion products corresponding to the current considered temperature is determined  $T_i$ .

Step 3. The enthalpies of combustion products  $I_i$  corresponding to the currently considered temperature are determined  $T_i$ . These quantities can be calculated using approximation polynomials.

Step 4. Using the values of the partial pressures as the values of the mole fractions of the corresponding gases included in the composition of the combustion products, their enthalpy is calculated  $I_{CP}$

$$I_{CP} = \sum_m (P_i \cdot I_i) \quad (15)$$

Step 5. The enthalpies of fuel and combustion products at the current temperature under consideration are compared. It should be taken into account that  $I_{CP}$  the values of partial pressures used for calculation are numerically equal to molar concentrations only in the case when  $M_T$  moles of fuel are considered. Enthalpies should be compared in the form of a ratio  $M_F \cdot I^{(F)} \Leftrightarrow I_{CP}$ .

Step 6. In the case of equality of these values or the permissible value of deviation, the temperature and composition of combustion products are considered determined. The calculation stops. Otherwise, proceed to the next item.

Step 7. Depending on the excess of the left or right part of the expression, the value of the current temperature  $M_F \cdot I^{(F)} \Leftrightarrow I_{CP}$  under consideration is

adjusted in the direction of its increase or decrease.  $T_i$  With the new value of the quantity,  $T_i$  we go to step 2 and repeat all the calculations.

## 4. The main part of the study

### 4.1. Simulation model of the MSW cleaning process during thermal destruction processing

In work [2], for various groups of solid waste, which are formed for the purpose of simulation modeling, the possibility of using the representation of the mixture of formed compounds by a conventional formula is proposed. In addition, it is proposed to classify MSW from various compounds included in each group. The averaged compounds in each group in the form of a conventional formula are presented in Table 1.

Table 1. Classified morphological composition of MSW by conventional formula.

Group name according to [1]	Group name according to [2]	The average composition of MSW for processing by thermal destruction methods
Hydrocarbons	A	$CH_{1,8}$
Hydrocarbons that contain oxygen	B	$CH_{1,7}O_{0,76}$
Hydrocarbons containing oxygen and nitrogen	C	$CH_{1,7}O_{0,76}N_{0,2}$
Hydrocarbons are those that contain active elements that form acid gases	D	$CH_{1,6}Cl_{0,76}F_{0,2}S_{0,44}$

Data processing [2] made it possible to obtain the following results on the morphological composition of MSW for Ukraine in 2018, namely: group A - 12%, B - 19%, C - 58%, D - 11%. Works [9,10,11,12] show the use of the simulation model (1-15) for simulating the processing of substances containing hydrocarbon compounds, including oxygen and nitrogen, by methods of thermal destruction. In [2], it is proposed to process solid waste of classes A, B, and C through combustion in an air atmosphere, and with class D, to carry out pyrolysis or gasification. In the same place, it is proposed to use chemical additives in class D solid

waste to minimize the formation of acid gases for linking active elements.

In [2] proposed a method of sorting MSW based on the definition of a simulation model in the form of a gross formula for the composition of MSW using the example of the morphological composition of MSW for the conditions of Ukraine. The result was obtained based on the method that identified the composition of solid waste by express gravimetric method. A capital letter indicates the result obtained in the form of a correct identification, a small letter indicates the number of compounds, received together, but under the condition of incorrect identification. The simulation results are presented in Table 2.

Table 2. Results of modeling the composition of solid waste when sorting by express gravimetric method according to the morphological feature of one species [2].

Starting mixture of averaged solid waste compounds	The result of sorting the starting mixture by the express gravimetric method	Conditional gross formula of each group of morphological composition after sorting the mixture
A = 120 CH <sub>1,8</sub>	A=108; b=2,6; c=7,9; d=1,5	CH <sub>1,799</sub> O <sub>0,034</sub> N <sub>0,005</sub> Cl <sub>0,009</sub> F <sub>0,035</sub> S <sub>0,008</sub>
B = 190 CH <sub>1,7</sub> O <sub>0,76</sub>	B=169; a=0,3; c=15,5; d=2,9	CH <sub>1,712</sub> O <sub>0,687</sub> N <sub>0,003</sub> Cl <sub>0,006</sub> F <sub>0,023</sub> S <sub>0,005</sub>
C = 580 CH <sub>1,7</sub> O <sub>0,76</sub> N <sub>0,2</sub>	C=501; a=4,7; b=7,7; d=43,2	CH <sub>1,974</sub> O <sub>0,453</sub> N <sub>0,177</sub> Cl <sub>0,006</sub> F <sub>0,025</sub> S <sub>0,005</sub>
D = 110 CH <sub>1,6</sub> Cl <sub>0,76</sub> F <sub>0,2</sub> S <sub>0,44</sub>	D=56,1; a=0,6; b=0,9; c=4,7	CH <sub>1,636</sub> O <sub>0,004</sub> N <sub>0,001</sub> Cl <sub>0,041</sub> F <sub>1,641</sub> S <sub>0,364</sub>
	a=6,3; b=10,1; c=50,9; d=6,2	CH <sub>1,799</sub> O <sub>0,024</sub> N <sub>0,004</sub> Cl <sub>0,006</sub> F <sub>0,025</sub> S <sub>0,006</sub>

Analysis of the results of Table 2 in the form of conditional gross formulas of each group of morphological composition after sorting the mixture shows that as a result of sorting it is not possible to obtain purified separated mixtures. In any mixtures there are impurities of solid waste compounds of class D, which means the presence of elements that

form acid gases. This state of affairs makes it impossible to directly burn separated compounds of classes A, B, C, since acid gases will be formed in the combustion products, and their excess is possible, which is regulated by environmental standards, which is unacceptable. Therefore, there are additional costs for cleaning combustion products from acid gases.

In [13], a formula was proposed for evaluating the efficiency of  $E_{installations}$  in which the process of solid waste combustion takes place in order to generate thermal or electrical energy for the consumer.

$$E = (E_p - (E_f + E_i)) / (0,97 \cdot (E_w + E_i)), \quad (16)$$

where  $E_p$  is the energy released to the consumer in the form of heat or electricity, GJ/year. This value is divided by the conversion efficiency of 0.91 when producing heat or by 0.38 when producing electricity;  $E_f$ - heat of additional fuel spent on energy production, GJ/year;  $E_w$ - heat of combustion of processed waste, GJ/year;  $E_i$ - energy obtained from an external source, GJ/year, 0.97 - an indicator for calculating heat losses for ash and flue gases.

In [13] it is noted that  $E_{does}$  does not characterize the thermodynamic efficiency, therefore, due to the efficiency of the conversion during the release of electricity and heat, this value can in some cases be greater than 1. Expression (15) makes it possible to determine the direction of the enterprise's activity or thermal processing of solid waste for the purpose of producing energy products, or simply for the thermal disposal of waste (reducing the volume of solid waste). The process of thermal processing of solid waste is considered utilization when the process index is 0.55 or less.

Expression (16) was slightly modernized to determine the efficiency of incineration of different groups of sorted solid waste as follows.

$$\varepsilon = E_p / (0,97 \cdot (E_f + E_{ii} + E_w + E_{ch})),$$

where  $E_p$  is the energy released to the consumer in the form of heat or electricity. The analysis was carried out with reference to the time of 1 hour for the production of 1 GJ of thermal energy. To comply with the dimensions, the consumption of solid waste of different groups was taken into account in the mass flow  $m$ , kg/h.  $E_w$ - heat of combustion of waste that is processed was calculated using the  $E_w = \sum [P_i \cdot (I_{CP} - I_{298})_i]$  expression Energy costs for dust removal and ash removal in evaluation units  $E_f$ . Electricity costs for the operation of cleaning systems,  $E_{ii}$ .  $E_{ch}$ - additional energy spent on the production of all chemical reagents required for cleaning flue gases to a state that corresponds to the maximum permissible concentrations, GJ/ hour.

The technological norm of permissible emissions in the case of burning in furnaces of untreated solid waste is established through the permissible emission (in accordance with Annex V of Directive EC/2000/76), which is measured in mass concentrations for: hydrogen chloride (HCl) 30 mg/m<sup>3</sup> and hydrogen fluoride (HF) 5 mg/m<sup>3</sup>, and for sulfur dioxide (SO<sub>2</sub>) at the level of 1800 mg/m<sup>3</sup>, as flue gases are normalized to a temperature of 0 °C (273.15 K) and a pressure of 101.32 kPa (without corrections for the content moisture or oxygen) [13].

After processing additional literary sources and conducting preliminary calculations, the results shown in Table 3 were obtained for evaluation during incineration in non-moist solid waste installations in compliance with environmental indicators .

Table 3. Combustion efficiency indicators of different groups of solid waste obtained during sorting.

	Hydrocarbon solid waste containing :			
	CH <sub>n</sub>	oxygen, CH <sub>n</sub> O <sub>m</sub>	oxygen and nitrogen, CH <sub>n</sub> O <sub>m</sub> N <sub>k</sub>	active elements: CH <sub>n</sub> F <sub>m2</sub> , CH <sub>n</sub> Cl <sub>m1</sub> , CH <sub>n</sub> S <sub>m3</sub>
E <sub>w</sub> , MJ/kg	45	18	30	35
m, kg/hour	22	56	33	26
E <sub>ii</sub> , GJ/hour	0,099	0,11	0,13	0,22
E <sub>f</sub> , GJ/hour	-	0,053	0,078	0,109
E <sub>ch</sub> , GJ/hour	-	-	0,098	0,31
ε	0,91	0,86	0,77	0,61

The efficiency indicator (ε) for the combustion of sorted solid waste through thermal destruction methods, specifically complete combustion in an air atmosphere, serves as a crucial factor in determining a decision-making rule for selecting the appropriate technical means for processing. Table 2 illustrates the outcomes after the initial sorting cycle of solid waste, revealing unnatural combinations.

Utilizing the ε criterion helps establish the boundary between two thermal destruction methods: incineration in the air atmosphere and pyrolysis for gas synthesis. Ideal conditions allow burning classified waste groups (A, B, C) in the air, with excess air coefficients for each group, adhering to emission regulations. However, classified waste group (D), containing substances generating acid gases, requires pyrolysis with a specific cleaning technology [1].

Analysis of Table 2 reveals the presence of acid gas-forming elements in any sorted waste group (A, B, C), typical of real waste sorting technologies [2]. Burning sorted waste in this case results in acid gas presence, necessitating a decision-making rule for the technical means in waste processing.

To determine acid gas amounts, the system of equations (1-13) must include components with acid gas-forming elements. However, solving this system led to instability and significant errors. Newton's method was considered but resulted in an ill-conditioned linearized system. As an alternative, estimating partial pressures based on the molar mass ratio of elements forming acidic compounds provided a more stable approach:

$$P_{HCl} = P_{\Sigma} \{M(Cl_{m1}) / M(CH_n O_m N_k Cl_{m1} F_{m2} S_{m3})\},$$

$$P_{HF} = P_{\Sigma} \{M(F_{m2}) / M(CH_n O_m N_k Cl_{m1} F_{m2} S_{m3})\},$$

$$P_{SO_2} = P_{\Sigma} \{M(S_{m3}) / M(CH_n O_m N_k Cl_{m1} F_{m2} S_{m3})\},$$

where: n , m , k , m 1, m 2, m 3 - the corresponding number of atoms of the substance in solid waste when sorting according to the morphological feature of one species, see table 2.

The number of atoms in MSW, which form acid gases, is calculated based on the number of considered molecules M<sub>F</sub> and partial pressure,

$$\text{for}[Cl] b_{Cl} \cdot M_F = P_{HCl};$$

$$\text{for}[F] b_F \cdot M_F = P_{HF};$$

$$\text{for}[S] b_S \cdot M_F = P_{SO_2}.$$

To determine the efficiency of burning different groups of sorted solid waste, in addition to ε, it is possible to use the expression for estimating the specific costs for processing 1 kg of solid waste, which contains elements that form acid gases, depending on the concentration of the i-th current sorted type Pr(MSW)<sup>i</sup>, with a correlation to the current specific price of natural of gas Pr(CH<sub>4</sub>), but for 1 kg.

$$Pr(MSW)^i = (1 - \epsilon_i) \cdot Pr(CH_4) \cdot C_{start}^i \cdot e^{((C_{lim}^i - C_{adj}^{jCYC}) / (C_{lim}^i - C_{start}^i))}$$

where: ε<sub>i</sub> –coefficient of combustion efficiency of the i-th group of solid waste; C<sub>start</sub><sup>i</sup> –the mass concentration of the i-th solid waste enters the first recycling cycle; C<sub>lim</sub><sup>i</sup> –the maximum possible mass concentration of the i-th MSW provided by the

sorting result;  $C_{adj}^{j\text{ cyc}}$  – intermediate mass concentration of the  $i$ -th MSW for the  $j$ -th cycle of increasing the mass concentration of the group after sorting the group under consideration.

#### 4.2. The decision-making rule for the formation of the structure of technical means in solid waste processing

The decision-making rule for forming the structure of technical means for choosing a method of processing solid waste by various methods of thermal destruction while complying with environmental indicators, the basis of which is the method of calculating costs for ensuring environmentally regulated indicators that use a simulation model of the cleaning process.

The main idea of the method is to model the costs of disposing of a given composition of solid waste, which contains a known number of elements that produce acid gases, weighing 1 kg, by the pyrolysis method and the direct burning method. For the correct compatibility of the results, the energy effect is reduced to the same value, taking into account the increase or decrease in costs for the disposal of acid gases. Then the specific indicator of the cost of a unit of energy production is recalculated for the same marginal provision of environmental emissions. The smallest indicator of the considered methods of thermal destruction, taking into account model errors, will be the criterion for choosing a decision rule. The equivalence of indicators within the considered error band indicates the equivalence of both methods.

Let's consider the costs of minimizing the impact of substances that generate acid gases in the components (by the pyrolysis method to obtain synthesis gas and by the combustion method in the boiler to generate thermal energy). Cleaning costs are calculated per 1 kg of treated solid waste component.

Mass concentration of substances that produce acid gases (kg/kg):

$$C_{acid} = m_{acid}/m_{comp},$$

where  $m_{comp}$  – 1 kg of the current component after sorting, ,

$m_{acid}$  – the mass of substances in the current component that form acid gases (kg).

The limit weight does not exceed 0.24 kg of substances that form acid gases, 1 kg of any component. Data obtained from the processing of the table. 2.

$C_{acid}^{lim}$  – the maximum permissible concentration of substances in the current component that generate acid gases during its

thermal processing, in accordance with the marginal regulatory environmental requirements.

$\Delta C_{max} = C_{acid} - C_{acid}^{lim}$  – change in concentration, which must be carried out by introducing an additional mass of neutralizing substance in the process of thermal processing

The mass of the neutralizing substance  $m_{neutr} = 2 \cdot m_{acid}$  is determined taking into account the molar masses and kinetic coefficients, which take into account the incompleteness of the neutralization reactions taking place.

Let's determine the maximum costs for neutralization of the acidic component in the range of concentration changes from  $C_{acid}$  to  $C_{acid}^{lim}$ . CaO (quick lime) is used to neutralize acidic components in thermal disposal technologies. Let's define compatible conventional monetary units (ConvMonUn) for 1 kg of CaO and 1 kg of methane gas.

The calorific value of methane gas is 55.3 (MJ/kg) and its cost per kg is 0.6 ConvMonUn /kg. The cost of 1 kg of CaO is  $Cost^{max} = 0.25$  ConvMonUn/kg. This ratio between the consumption of gas and CaO should be approximately observed, since the production of CaO requires a proportional consumption of methane gas. The output from the presented data, taking into account the manufacturability of the application, provides the maximum costs for various components:  $Cost_{comp}^{max} = var_{comp}^i \cdot Cost^{max}$ . The indicators are empirical in nature and were obtained by data processing:

The indicators are empirical in nature and were obtained by data processing :

$$var_{comp}^A = 0,29; var_{comp}^B = 0,35;$$

$$var_{comp}^C = 0,67; var_{comp}^D = 1.$$

Suppose, as a result of thermal processing, for certain reasons, it cannot be achieved  $C_{acid}^{lim}$  – permissible concentration of substances. In this case, the costs for obtaining an intermediate concentration value  $C_{acid}^i$  (for example,  $C_{acid}^A = 0.025$  (kg/kg) when processing 1 kg of component A) are determined as follows:

$$Cost_{comp}^i(C_{acid}; C_{acid}^i) = Cost_{comp}^{max} \cdot$$

$$C_{acid}^i / \Delta C_{max} \cdot e^{\frac{\Delta C_{max} - C_{acid}^i}{\Delta C_{max}}}.$$

As a result of all the limitations and assumptions that have been adopted, the expression can be used for substances that form acid gases, with a value of the concentration value from the maximum permissible to the minimum value, which is 0.5% by weight of the component under consideration.

Let's consider the following provisions that determine the costs of removing acid gases from synthesis gas to bring their concentration to an environmentally safe norm. Also costs for cleaning flue gases coming from the boiler into the natural environment.

The task is solved for the purification of 1 kg of synthesis gas or flue gas. As a result of the analysis of literature data, it is customary to carry out cleaning through a dry bag filter. The filter material is nitron. The cost of the sleeve is 1900 ConvMonUn /t, and the adsorbent, as before, is CaO. The task is solved in mass concentrations. Now the calculation of the cost of cleaning one kilogram of synthesis gas or flue gas is carried out from the residual concentration of substances that form acid gases, the residual amount of which is 75% of the initial value (this value is determined based on the analysis of the literature on the purification of pyrolysis gases), because 25% of substances that form acid gases remain in the sludge.

The marginal maximum value  $C_{gas}^i$  may exceed the value of 0.18 kg/kg.

$\Delta C_{max} = C_{gas}^i - C_{gas}^{lim}$  — change in concentration, which must be carried out by introducing an additional mass of neutralizing substance into the bag filter. The concentration of gases is brought to the limit, which ensures environmental safety  $C_{gas}^{lim}$ .

In a bag filter for the purification of one kilogram of pyrolysis synthesis gas or one kilogram of flue gases for the calculated change in concentration to the norm that ensures environmental safety, in addition to the already known costs for 1 kg of CaO  $Cost^{CaO} = 0.25$  ConvMonUn/kg, additional costs for the material are required (for example, nitron). The service life of the bag filter is also taken into account, calculated for 1 kg of gas being cleaned  $Cost^{BF} = 0.1$  ConvMonUn /kg.

Based on the processed data, taking into account the manufacturability of cleaning, the maximum costs for cleaning acid gases are determined:

$$Cost_{acid}^{max} = var_{acid}^i \cdot (Cost^{CaO} + Cost^{BF}).$$

Indicators are empirical in nature and were obtained as a result of data processing:

$$var_{acid}^{HF} = 1; var_{acid}^{HCl} = 0,05; var_{acid}^{SO} = 0,065.$$

$$Cost_{acid}^i(C_{gas}^i) = Cost_{acid}^{max} \cdot \frac{C_{gas}^i}{\Delta C_{max}} \cdot e^{-\frac{\Delta C_{max} - C_{gas}^i}{\Delta C_{max}}}.$$

### 4.3. Complex technological scheme of thermal destruction methods in solid waste processing

A complex technological scheme of thermal destruction methods during MSW processing is presented in Fig. 1.

A vibratory separator or shaker (1) is employed for filtering fine fractions of PVC: soil, dust, etc. Following this, a magnetic separator (2) automatically extracts magnetic steel materials, directing them to a bunker (3). Eddy current separator (color metal separator) (4) is used for automatic selection of non-magnetic metals such as copper, aluminum, etc., directing them to a bunker (5). Cyclone separator (6) separates silicate fragments of PVC, directing them to a silicate materials bunker (7).

In the next stage, MSW proceeds to the crushing plant (8). Prepared MSW then enters a receiving dosing bunker (9), from which a portion of the mixture is sent to a sorting unit based on qualitative analysis (10). Here, the mixture is separated based on morphological composition and distributed into four bunkers, depending on the prevalence of components A (11), B(12), C(13), or D(14).

During isothermal decomposition, four specific groups (A, B, C, D) that make up the total volume of solid waste can form 11 variants of different mixtures, which are identified in the sorting block, based on quantitative analysis (15), and are distributed depending on the results of the analysis one of the bunkers: bunker of solid waste of mixture group A (16.1), bunker of solid waste of mixture group B (16.2), bunker of solid waste of mixture group C (16.3), bunker of solid waste of mixture group A+B (16.4), bunker of solid waste of mixture group A+C (16.5), bunker MSW of mixture group B+C (16.6), bunker of MSW of mixture group A+B+C (16.7), bunker of MSW of mixture group A+D (16.8), bunker of MSW of mixture group B+D (16.9), bunker of MSW of mixture group C+D (16.10), solid waste bunker of mixture group A+B+D (16.12), solid waste bunker of mixture group A+C+D (16.13), solid waste bunker of mixture group B+C+D (16.14), solid waste bunker of group A+B+C+D mixture (16.15).

This method of identification makes it possible to distinguish two groups: those that produce and do not produce acid gases during combustion.

Let's consider the stages of thermal utilization of MSW of the first group, which do not produce acid gases during combustion. Mixtures from bunkers (16.1-16.7) forming this group are sent to

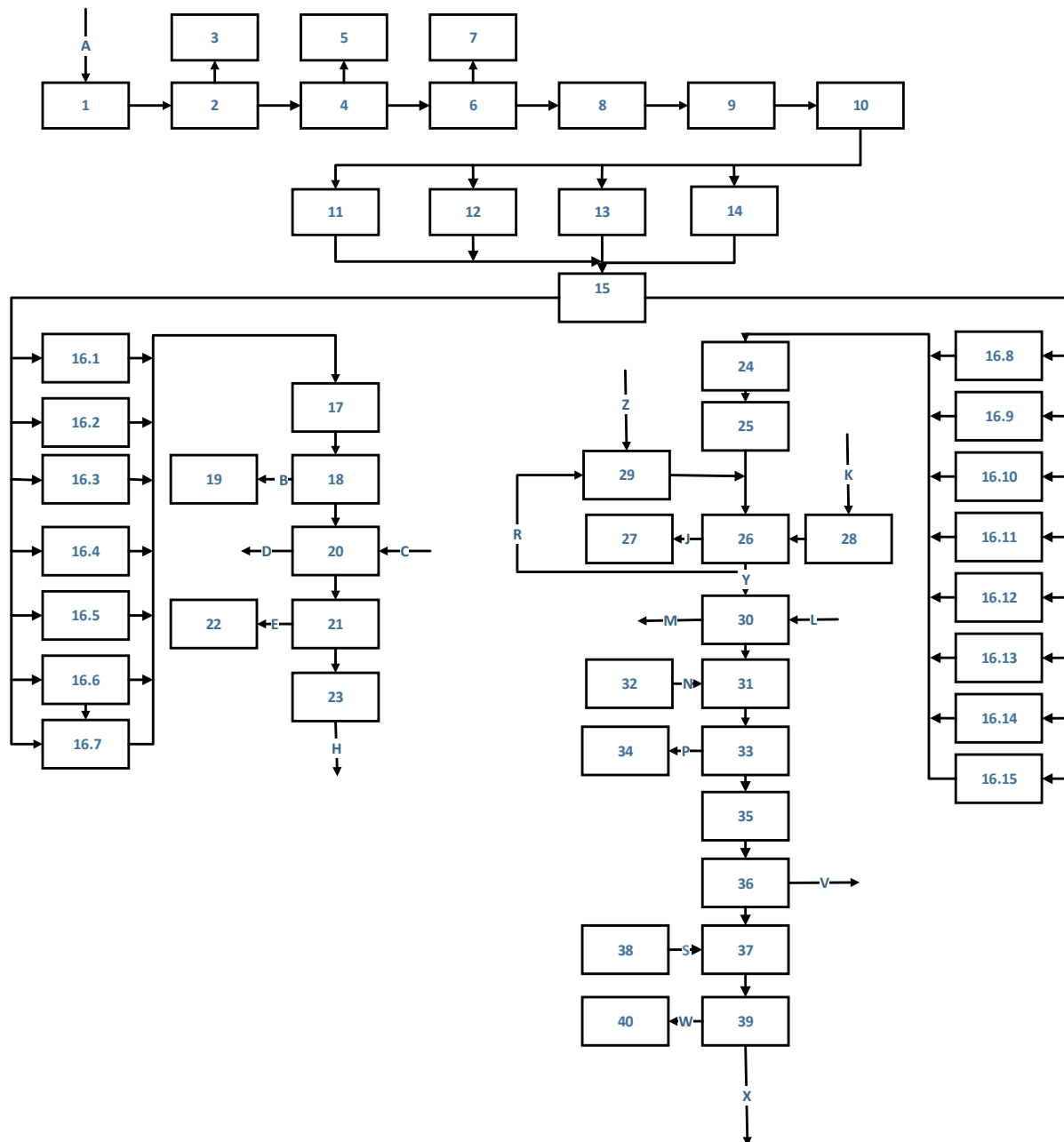


Fig. 1. Complex technological scheme of thermal destruction methods during MSW processing.

the dosing bunker (17) of solid waste components. Then - to the incinerator (18). After thermal destruction, a carbon residue (B) is formed, which is sent to the bunker (19), and flue gases, which are used to heat water (20), and then undergo purification. We will use flue gas purification, which includes mechanical filtration in a cyclone (21). Dust settles in the lower part of the housing and then enters the storage hopper (22). This is followed by an exhaust fan (23), which directs the deoxidized product gas into the atmosphere (H).

Let's consider the stages of thermal utilization of solid waste of the second group, which generate acid gases during combustion. Mixtures from bunkers (16.8-16.15) forming this group are sent to the dosing bunker (24) of the solid waste component. Next - an intermediate bunker (25), the bottom of which is a plate feeder designed for loading MSW into the pyrolysis furnace (26). In addition, an alkaline compound CaO or Na<sub>2</sub>O (K) is supplied to the pyrolysis furnace from the bunker of soluble materials (28). Regenerative heated air (Z) is

supplied from the air heater (29) to the pyrolysis furnace. At the same time, the pyrolysis gas formed is divided into 2 streams: which is supplied to the consumer (Y); and which enters the recirculation line at the entrance to the reactor for drying and preheating MSW (R). Solid carbon product - carbon residue (J) is sent to the bunker (27). Pyrolysis gas (Y) is used to heat water (30), and then it is purified.

At the initial concentrations of acidic gases ( $\text{SO}_3$ ,  $\text{HCl}$ ,  $\text{HF}$ ) in the product gas, it is purified by the sorption method, by controlled introduction of dry powder  $\text{Ca}(\text{OH})_2$  or  $\text{Na}_2\text{CO}_3$  (N) directly into the gas pipeline into the device from the bunker (32) narrowing (31). This is followed by treatment in a cyclone with a bag filter (33) and filtration of sorption products and dust removed from the pyrolysis furnace (P) of solid particles into a bunker (34).

The exhaust fan (35) prevents the leakage of untreated flue gases into the environment and its diffuse distribution. The gas is supplied to the diesel generator (36) and the electricity (V) produced is supplied to the consumer. At the exit from the generator, additional purification of gases takes place by the sorption method by controlled introduction of dry powder  $\text{Ca}(\text{OH})_2$  or  $\text{Na}_2\text{CO}_3$  (S) from the bunker (38) directly into the gas pipeline in the narrowing device (37). This is followed by treatment in a cyclone with a bag filter (39). The sorption products (W) follow into the bunker (40), the purified gas (X) – into the atmosphere.

## 5. Research results

On the basis of a modified model of the cleaning process, which takes into account the costs of sorbents to bring the obtained carbon-hydrogen gases from the classified MSW of the main group to an environmentally acceptable state, the following results were obtained for the cleaning of sorted groups of MSW (see Table 2).

These are the results of simulations of acid gas purification by various methods based on (HF), (HCl) and ( $\text{SO}_2$ ). They are obtained by pyrolysis due to the minimum permissible rationing in the emission (see 5.1).

Figure 2 shows the dependence of Cost on sorbents for purification of processing sludge during pyrolysis on the initial specific concentration of acid gas (HF)  $C_{\text{кисл}}$ . The solid waste was pre-sorted. Calculations are presented for 1 kg of gas obtained. The depth of its cleaning corresponds to environmental regulations.

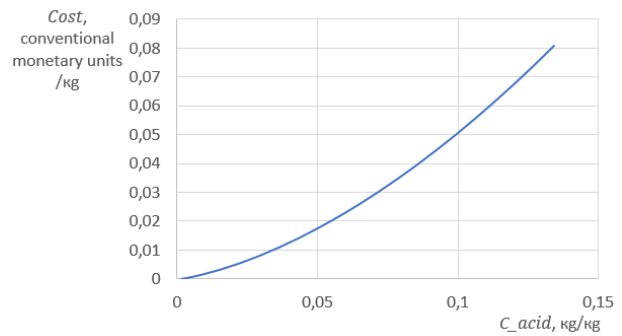


Fig.2 Results of modeling of acid gas purification based on (HF) using a sorbent in the process of thermal processing in the process of pyrolysis.

According to the simulation results, we can see that if the solid waste sludge contains 0.13 kg of substances that form acid gases, which must be sorbed so that their concentration at the outlet is close to zero, then for this it is necessary to spend about 0.08 conventional value units purchase of absorbent.

If solid waste sludge containing 0.13 kg of substances that form acid gases needs to be sorbed so that only 0.07 kg of them are contained in 1 kg of the obtained gas, then for this it is necessary to spend about  $0.08 - 0.03 = 0.05$  conditional value units for the purchase of absorbent.

Figure 3 shows the dependence of Cost on sorbents and a bag filter for cleaning 1 kg of gas obtained during the pyrolysis of MSW on the initial specific concentration of acid gas (HF)  $C_{\text{кисл}}$ . The depth of cleaning corresponds to environmental regulations.

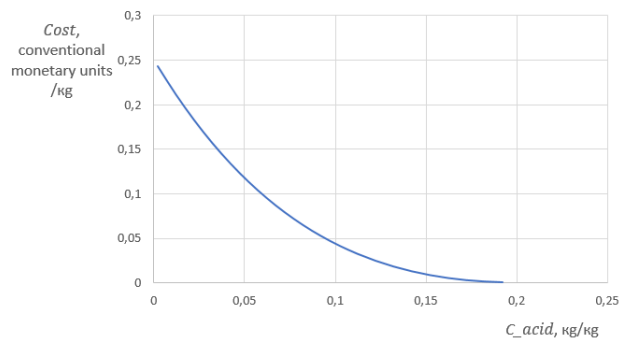


Fig. 3 Results of simulation of cleaning from acid gas, which is based on (HF) using a bag filter and a sorbent.

Based on the simulation results, it is possible to determine if 1 kg of the obtained gas contains 0.19 kg of substances that form acid gases, which must be sorbed in a bag filter so that their concentration at the outlet is close to zero or does not exceed the environmental regulation in this regard species For

this, it is necessary to spend about 0.25 conventional value units to ensure the operation of the sleeve filter.

If 1 kg of the obtained gas, containing 0.19 kg of substances that form acid gases, must be partially sorbed in a bag filter so that at the outlet there is a concentration of 0.05 kg of acid gas, for this it is necessary to spend about  $0.25 - 0.12 = 0.13$  conventional value units for ensuring the operation of the bag filter.

In fig. 4 shows the results of a model purification experiment obtained during the pyrolysis of solid waste 1 kg of acid gas (HF), using two methods simultaneously.

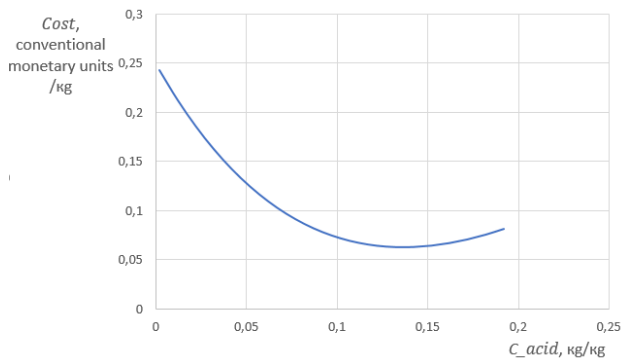


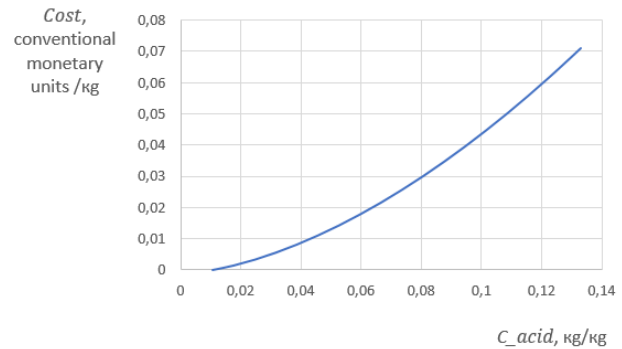
Fig. 4. Results of modeling of acid gas purification based on (HF) using a sorbent in the process of thermal processing using two methods at the same time.

The experiment consists of several stages. At the first stage, Cost is determined for sorbents for processing sludge cleaning. The condition for reducing the amount of acid gases is found in the mass concentration by the value of  $\Delta C_{\text{кисл}}$ , in this case by 0.01. In the second step, the cost of sorbents and a bag filter is determined to further purify the obtained 1 kg of gas from the residual acid gas concentration to zero or a value close to the environmental regulations. Then the costs are summed up.

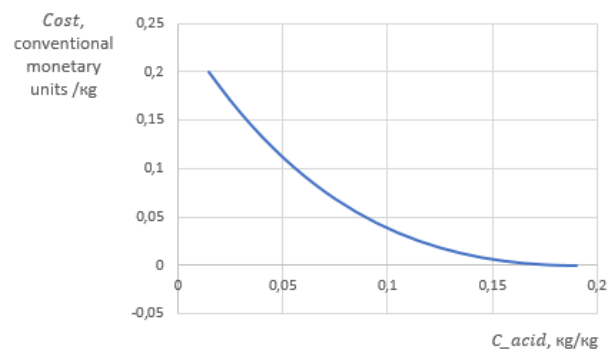
The same model calculation is performed at all subsequent steps. At each step, the concentration of acid gases decreased during pyrolysis. The costs due to the addition of sorbents to the sludge increased, and the costs of gas purification with sorbents in the bag filter led to the required concentration.

Thus, all options between the two limit models of cleaning were investigated, the results of which are presented in Fig. 2 and 3. Such a computational experiment showed that for the mixed technology there is a best point from the point of view of acid gas purification in, when it is possible to use different methods of purification.

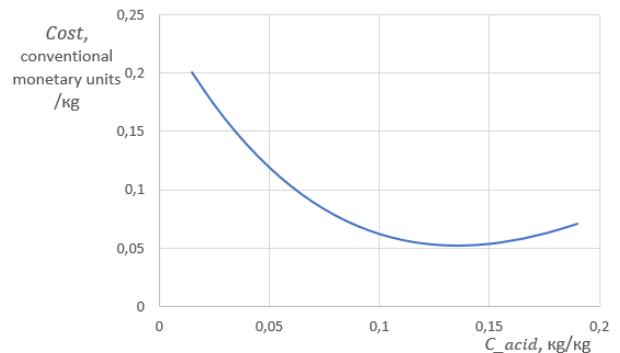
A similar computational experiment was conducted for the purification of acid gases (HCl) and (SO<sub>2</sub>). The results are presented in fig. 5.



a.



b.



c.

Fig. 5. Modeling results for cleaning acid gas based on (HCl) and (SO<sub>2</sub>) using a sorbent in the process of thermal processing in the process of pyrolysis (a) using a bag filter and sorbent (b) using two methods at the same time (c).

## Conclusions

In order to carry out processing of solid waste by thermal destruction methods with the production of carbon-hydrogen gases in compliance with ecological indicators, a simulation model of the cleaning process is proposed, which consists of calculations:

1. the indicator of the efficiency of combustion of various groups of sorted solid waste, which is one of the criteria for choosing between two possible methods of processing when using thermal destruction technology: combustion of solid waste in an air atmosphere or pyrolysis with obtaining gas synthesis and its further use.

2. additional costs for cleaning combustion products from acid gases, because the results of modeling the composition of solid waste when sorting by the express gravimetric method according to the morphological feature of one species showed that in any mixtures there are impurities of elements that form acid gases. When modeling costs, the energy effect was reduced to the same value and the same marginal value of environmental emissions was ensured.

Based on the developed simulation model, a decision-making rule for forming the structure of technical means for solid waste processing is proposed. A comprehensive technological scheme of the thermal utilization method has also been developed

This approach makes it possible to optimize solid household waste processing processes taking into account efficiency, resource intensity and compliance with environmental standards.

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## МОДЕЛЬ І МЕТОД ПРАВИЛА ПРИЙНЯТТЯ РІШЕННЯ ДЛЯ ФОРМУВАННЯ СТРУКТУРИ ТЕХНІЧНИХ ЗАСОБІВ В ПРОЦЕСАХ ТЕРМІЧНОЇ ДЕСТРУКЦІЇ ТПВ ПРИ НОРМУВАННІ ВИКИДІВ КИСЛИХ ГАЗІВ.

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**Анотація.** Розроблено імітаційну модель процесу очищення класифікованих ТПВ, що враховує витрати ресурсів на приведення отриманих вуглецево-водневих газів із класифікованих ТПВ основної групи в стан екологічно допустимий, який забезпечить облік домішок груп, що утворюють кислі гази для різних умов проведення переробки методами термічної деструкції. Запропоновано правила прийняття рішення на формування структури технічних засобів з метою переробки ТПВ методами термічної деструкції. Представлено комплексну технологічну схему методу термічної утилізації, що забезпечує дотримання екологічних умов на викиди у навколишнє середовище, при використанні вторинних енергетичних ресурсів, отриманих з ТПВ.

**Ключові слова:** тверді побутові відходи, термічна деструкція, піроліз, спалювання, кислі гази.

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