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Investigation of the energy efficiency of waste utilization technology, with considering the use of low-temperature separation of the resulting gas mixtures

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Currently, there are existing technologies for high-temperature waste disposal, which use the resulting gas as fuel for recycling newly formed waste. However, the composition of waste is not constant, and contents of their components are different, thus, the need for fuel gas for burning is not stable. Therefore, such gas is constantly lost. Thus, the purpose of the article is to present the study results of the energy efficiency of high-temperature waste disposal technology, which includes low-temperature separation of the resulting gas mixtures, which allows accumulating fuel products. By means of numerical simulation an analysis of the functioning of energy-technological facility of separation of multicomponent hydrocarbon mixtures with the subsequent optimization of its parameters in order to improve its efficiency and decrease energy costs for waste gasification was performed. For this purpose, the classical approach and generally accepted thermodynamics relations were used, including the Peng-Robinson equation of state for the description of coefficients of heat-physical characteristics of working bodies. The complexity of calculation of multicomponent systems (with three and more components) does not allow application of the state diagrams. Thus, for the simulation of heat-physical characteristics the REFPROP program was employed. The energy efficiency of the proposed technology of energy resources production at waste utilization was shown. The amount of products obtained by the facility is equal to 5.242 kg/hour of the fuel product No. 1 with methane content of 99.98% and 54.76 kg/hour of the fuel product No. 2 with low quantity of methane. This confirms the economic efficiency of such technology of disposal.

Keywords: wastes, waste utilization, synthetic gas, energy characteristics

INTRODUCTION

The development of new technologies and manufacturing processes is conditioned by the raise of requirements applied to materials and products made out of them. However, any manufacturing process is accompanied both by the harmful emission in the atmosphere [1–3] and waste generation [4, 5] leading to heavy metals accumulation in soil [6, 7]. There are many modern technologies of utilization of different sorts of wastes [8–10] which allow to obtain raw materials for energy generation [11]. However, waste treatment in most cases is reduced down to waste dumping [12]. Since waste decomposition processes take place in limited periods on bounded territories, we observe high intensity of dangerous molecular compositions emission to the atmosphere [12] with the occurrence of unintentional fires [13, 14], thus, investigations on the assessment of civil protection units' readiness to actions during extreme situations are taken [15, 16]. To avoid dumping of wastes not suitable for recycling, the preferences must be given to high-temperature ways of waste disposal such as incineration, pyrolysis and gasification, because high-temperature waste disposal with the aim of obtaining energy that can be used is a promising and relevant direction. It is important to understand the energy efficiency of high-temperature waste disposal.

In works [18–20] they have proven experimentally that waste utilization plasma technology application provides synthetic gas with calorie characteristics higher than those at traditional technology usage. In work [21] they have compared energy efficiency obtained at 1400 K temperature regime at waste utilization using processes of plasma and autothermal gasifications. There they have shown that with the existing methods of energy conversion the additional synthetic gas energy output obtained with plasma generators is not able to cover real costs of consumed electrical power. Vegetable and food wastes may be utilized by composting with special mineral additives [22], by means of decomposition in biogas equipment installations with subsequent thermal treatment of fermented residue in a pyrolysis furnace [23]. However, for unsorted solid municipal wastes such ways of utilization are technologically and economically inexpedient. This is due to the fact that the composition of the waste is not manageable, and the amount of waste depends on seasonality and the number of people in the city (village, etc.). At the same time, energy consumption during the day is not constant. This means that under different conditions a different amount of energy is produced which must be used or accumulated.

High-temperature waste recycling methods application allows obtaining synthetic gas, the composition of which includes not only carbon monoxide (CO) and hydrogen (H_2) but also such components as carbon dioxide (CO_2), nitrogen oxides (NO_x), a small amount of methane (CH_4), ethylene (C_2H_4), etc. The obtained low-calorie gas is used for direct combustion to produce heat both for domestic and electrical power generation needs. Due to the receipt of energy in the immediate vicinity of the place of use, this approach avoids losses during the transportation phase [17]. However, firstly, the resulting low-calorie gas is not enough to ensure the high-temperature disposal of waste, as mentioned above. Secondly, the receipt of waste and its composition is not constant, thus the need for fuel gas for burning is not constant. Also, the average daily and seasonal heat (energy) consumption is not constant. In that, when waste is not received for utilization, this gas is not used, does not accumulate and, therefore, is lost. Then it was proposed to use high-temperature waste disposal technology, which includes low-temperature separation of the resulting gas mixtures, which allows you to accumulate fuel products.

In works [24, 25] authors have proposed the technology of high-temperature waste utilization that allows to avoid the loss of heat and energy (which are occurring with uneven consumption) by creating fuel products suitable for storage and subsequent sale. This technology covers the following processes: thermochemical gasification; plasma post-combustion of produced gases; sharp cooling of gases; preliminary gas cleaning; gas methanation; final cleaning of produced gases; low-temperature separation of synthetic gas into fuel products. In the proposed waste utilization technology the reactor is made up of two chambers, one of which is the gasification reactor, and the other is the plasma reactor (Fig. 1).

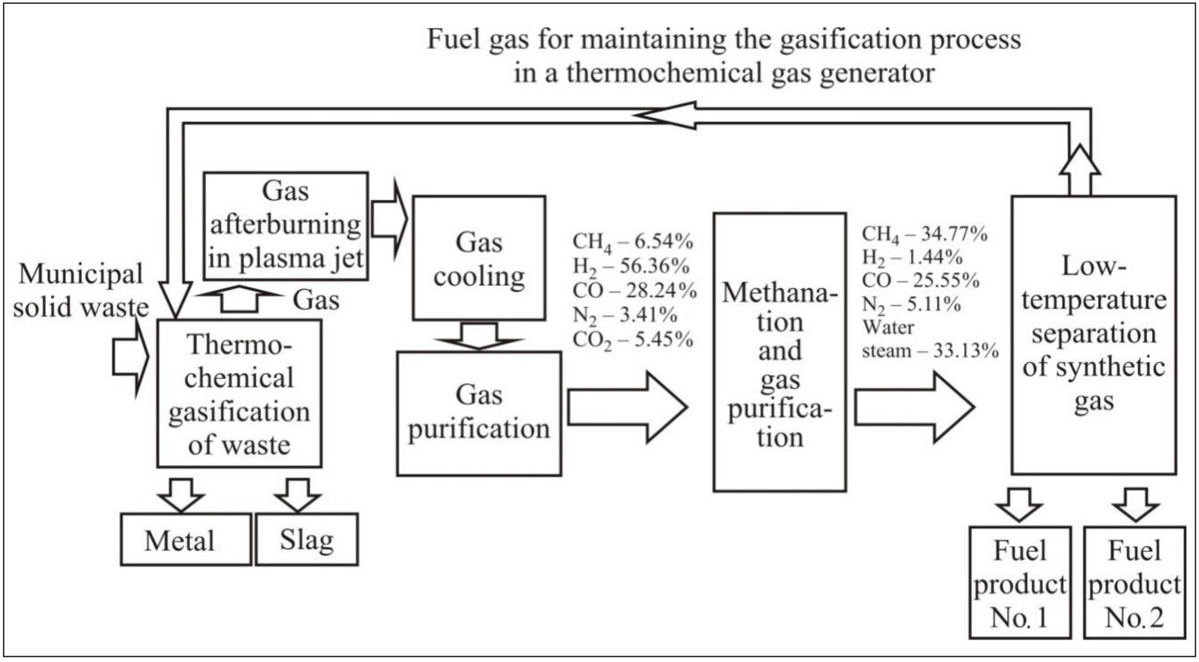

Fig. 1. Scheme of the sequence of technological stages of waste disposal

At first we carried out the process of high-temperature waste gasification and then the steam-gas mixture was processed in the plasma jet. Such stepwise waste treatment reduces energy consumption, due to the fact that in a plasma reactor only the resulting gas, but not the whole mass of solid waste is processed. In the process, air was used as the main gasifying agent. As raw material, municipal solid waste was adopted, for which the average component composition was determined by statistical analysis [26]. After thermochemical gasification of waste, afterburning of exhaust gas in plasma [24], cooling of this gas [10], and necessary purification and enrichment of this gas with methane [25], the synthesis gas obtained enters for low-temperature separation to obtain fuel products of a given quality. As a result of the separation process, liquefied methane, liquefied methane-containing gas and fuel gas for heating, generating electricity or maintaining the gasification process in a thermochemical gas generator are formed. The basic scheme of the process of low-temperature separation of the gas mixture is shown in Fig. 2 [29].

After purification, the gas is dried in the block of adsorption drying (not shown in the scheme) and compressed in the C-1 compressor with a subsequent cooling in the air cooler AC to the ambient temperature. Next, the gas is divided into 3 streams and sent to the heat exchangers HE-1, HE-2, HE-3 for cooling backflow products. After combining all three streams, the gas enters the separator S, where the liquid phase is separated (product No. 2). Then the pressure of the obtained liquid product in the pump P-1 rises to 22 MPa. The gaseous phase from separator S is cooled in the heat exchanger HE-4 and fed to the rectification column RC. From the condenser of the column in the upper part, gaseous product No. 1 is removed, which is a mixture of CO, H_2, and N_2. This gas, passing through the expander part of the wave expander compressor (WEC), performs the expansion work, which is used to compress part of the source gas parallel to the C-1 compressor. In the return flow, this gas passes through the HE-5, HE-4 and HE-1 heat exchangers, cooling successively the product No. 3 and the direct flow of the incoming gas. From the reboiler of the RC rectification column, product No. 3 enriched in methane is removed, which is compressed by a pump to a pressure of 22 MPa and heated in the heat exchanger HE-3, after which it can be accumulated as a compressed gas.

The purpose of the article is to present study results on the energy efficiency of such waste utilization technology which includes low-temperature

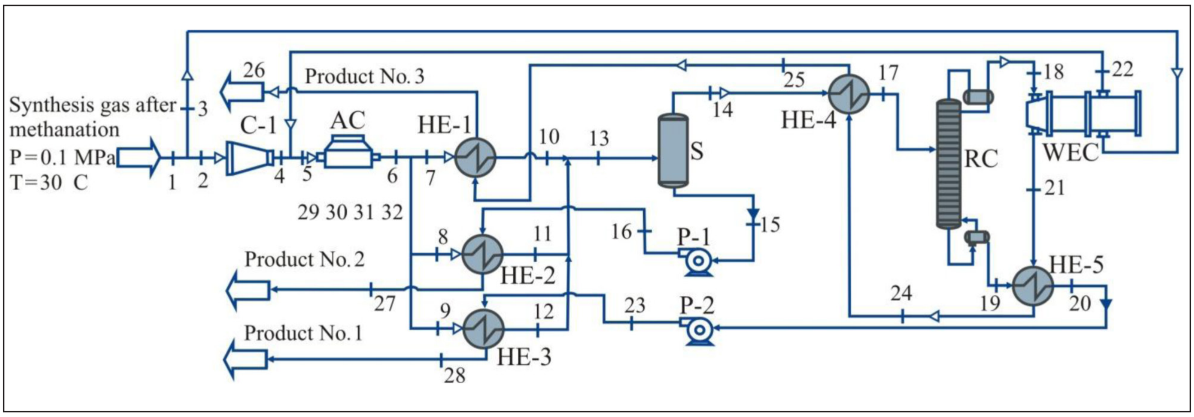

Fig. 2. The basic scheme of the process of low-temperature separation of the multicomponent hydrocarbon gas mixture [29]: C-1 – compressor; AC – air cooler; HE-1, HE-2, HE-3, HE-4, HE-5 – heat exchanger; P-1, P-2 – pump; S – separator; RC – rectification column; WEC – wave expander compressor

separation of the resulting gas mixtures, which allows to accumulate fuel products.

MATERIALS AND METHODS

By means of numerical simulation an analysis of the functioning of the energy-technological facility of separation of multicomponent hydrocarbon mixtures with the subsequent optimization of its parameters in order to improve its efficiency and decrease energy costs for waste gasification was accomplished.

For this purpose, the classical approach and generally accepted thermodynamics relations, including the Peng-Robinson equation of state for the description of coefficients of heat-physical characteristics of working bodies were used. The complexity of calculation of multicomponent systems (with three and more components) does not allow application of the state diagrams. Thus, for the simulation of heat-physical characteristics the REFPROP program was employed. To solve the system of non-linear equations the Newton-Raphson iteration method was used.

RESULTS AND DISCUSSION

In works [27, 28] authors have proposed the technique of calculation for each element of the low-temperature separation circuit and described initial parameters and assumptions.

The complexity of the processes taking place in the rectification column does not allow creation of both a detailed and relatively simple mathematical model for rectification column parameters calculation. Thus, we use a black box model to describe rectification column functioning. We set multicomponent flow in the inlet of the rectification column with the known temperature T_{RC_IN}, pressure P_{RC_IN} and consumption G_{IN}. With such initial data the set of subprograms designed for the calculation of coefficients of heat-physical characteristics of working bodies allows to obtain mass and molar composition of steam and liquid phases of the flow supplied in the inlet of the rectification column together with specific enthalpy of the flow. For the mathematical model of the rectification column we used the following assumptions [27]:

- the value of hydraulic losses in the rectification column is taken to be equal to zero;
- the heat exchange between structural elements of the rectification column is neglected;
- the pressure inside the column cube is taken to be higher than the one inside the condenser;
- the value of the rectification column feed pressure is taken to be in between the values mentioned above;
- the adjustment of the component composition of the products is made both by heat supply in the reboiler and heat removal in the condenser.

To describe the functioning of the rectification column we may use the following system of equations:

$$G_{IN} = G_{L\_OUT} + G_{V\_OUT}, G_{IN} \cdot i_m(P_{RC\_IN}, T_{RC\_IN})$$
$$= G_{L\_OUT} \cdot i_m(P_{L\_OUT}, T_{L\_OUT}) + Q_{RB} \qquad (1)$$
$$+ G_{V\_OUT} \cdot i_m(P_{L\_OUT}, T_{V\_OUT}) - Q_{COND,}$$

where g_{L_OUT}, g_{V_OUT} are consumption values in the rectification column outlet for single-phase liquid and gas products, correspondingly; i_m is specific enthalpy of multicomponent mixture calculated for the given composition by means of the set of subprograms designed for the calculation of heat-physical characteristics coefficients; T_{L_OUT}, P_{L_OUT} are temperature and pressure values, correspondingly, for liquid product in the reboiler outlet; T_{V_OUT}, P_{V_OUT} are temperature and pressure values, correspondingly, for gas product in the condenser outlet; Q_{RB} is heat supplied for the reboiler; Q_{COND} is heat removed from the condenser.

Component compositions of the inlet and outlet products are connected with the following system of equations:

$$\begin{cases} G_{IN} \cdot g_{IN\_1} = G_{L\_OUT} \cdot g_{L\_OUT\_1} + G_{V\_OUT} \cdot g_{V\_OUT\_1}, \\ G_{IN} \cdot g_{IN\_2} = G_{L\_OUT} \cdot g_{L\_OUT\_2} + G_{V\_OUT} \cdot g_{V\_OUT\_2}, \\ G_{IN} \cdot g_{IN\_3} = G_{L\_OUT} \cdot g_{L\_OUT\_3} + G_{V\_OUT} \cdot g_{V\_OUT\_3}, \\ \dots\dots\dots\dots\dots\dots \\ G_{IN} \cdot g_{IN\_n} = G_{L\_OUT} \cdot g_{L\_OUT\_n} + G_{V\_OUT} \cdot g_{V\_OUT\_n}, \end{cases} \qquad (2)$$

where g_{IN_i}, $g_{L\_OUT\_i}$, $g_{V\_OUT\_i}$ are mass fractions of the i-th component in the rectification inlet, reboiler outlet and condenser outlet, correspondingly.

The calculation of rectification column parameters is made by the method of successive approximations [27]. Depending on the required value of mass content of the component the set of iterations is accomplished for given values of pressure inside the reboiler and condenser by means of the set of subprograms designed for the calculation of coefficients of heat-physical characteristics of working bodies. The initial value of mass content of steam and liquid phases is found using the column inlet parameters. Then for each iteration the system of equations (2) is recalculated for varying values of temperature inside the reboiler T_{L_OUT} and condenser T_{V_OUT}. The calculation process is completed when the previously set mass content value is obtained for certain component with the required accuracy. After that they calculate the values of heat supply in the reboiler Q_{RB}, heat removal from the condenser Q_{COND}, and mass consumption of liquid and gas phases.

Using the set of subprograms designed for the calculation of coefficients of heat-physical characteristics of working bodies based on the Peng-Robinson equation of state [27] we calculate mass composition of liquid and gas phases:

$$g_{CO\_14}, g_{H_2\_14}, g_{CO_4\_14}, g_{N_2\_14}$$
$$= f_6(P_{13}, T_{13}, g_{CO\_13}, g_{H_2\_13}, g_{CH_4\_13}, g_{N_2\_13}), \qquad (3)$$

$$g_{CO\_15}, g_{H_2\_15}, g_{CO_4\_15}, g_{N^2\_15}$$
$$= f_6(P_{13}, T_{13}, g_{CO\_13}, g_{H_2\_13}, g_{CH_4\_13}, g_{N_2\_13}). \qquad (4)$$

According to the results of calculations, three flows of energy resources may be obtained. The flows with a high mass content of methane of 91.53% (control section 28, Fig. 2) and 83.48% (control section 27, Fig. 2) are compressed products and they may be used both as motor fuel (analogue of compressed automobile natural gas). The gas flow obtained in control section 26 (Fig. 2) is suitable for maintaining the process of gasification of waste (Table 1).

It is obvious that the proposed scheme of the low-temperature separation of multicomponent hydrocarbon mixtures satisfies conditions of the task. Yet a more efficient alternative may be found. For example, according to the results in the condenser of the rectification column RC it is required to use the refrigerant with the temperature less than –182 0176C allowing to remove heat power of 2.836 kW. Liquid nitrogen meets requirements on temperature level. At normal conditions the value of hidden evaporation heat is equal to Ψ = 197.6 kJ/(kg·K), then refrigerant consumption is equal to 51.7 kg/hour. Liquid nitrogen usage can be excluded if the condenser is not included in the composition of the column. Then the costs value will decrease. However, in such case, as it may be proven with the numerical simulation results, there will be no opportunity to separate the whole amount of methane from the “top” flow. The scheme of such alternative

Table 1. **Mass fraction of the components of the hydrocarbon gas mixture in the control sections**

Control section	Pressure, MPa	Temperature, °C	Consumption, kg/h	Mass composition of the product			
				CH_4	H_2	CO	N_2
1	0.1	30	60.0	0.3756	0.0196	0.4287	0.1761
2	0.1	30	54.0	0.3756	0.0196	0.4287	0.1761
3	0.1	30	6.0	0.3756	0.0196	0.4287	0.1761
4	0.6	250.7	54.0	0.3756	0.0196	0.4287	0.1761
5	0.6	250.7	60.0	0.3756	0.0196	0.4287	0.1761
6	0.6	30	60.0	0.3756	0.0196	0.4287	0.1761
7	0.6	30	16.8	0.3756	0.0196	0.4287	0.1761
8	0.6	30	9.0	0.3756	0.0196	0.4287	0.1761
9	0.6	30	34.2	0.3756	0.0196	0.4287	0.1761
10	0.6	−168.1	16.8	0.3756	0.0196	0.4287	0.1761
11	0.6	−130.6	9.0	0.3756	0.0196	0.4287	0.1761
12	0.6	−119.7	34.2	0.3756	0.0196	0.4287	0.1761
13	0.6	−150.4	60.0	0.3756	0.0196	0.4287	0.1761
14	0.6	−150.4	55.21	0.3358	0.0212	0.4553	0.1877
15	0.6	−150.4	4.79	0.8347	0	0.1228	0.0424
16	22.0	−135.6	4.79	0.8347	0	0.1228	0.0424
17	0.6	−151.8	55.21	0.3358	0.0212	0.4553	0.1877
18	0.596	−177.5	35.04	0.0023	0.0335	0.6782	0.2860
19	0.6	−140.7	20.17	0.9152	0	0.0679	0.0168
20	0.6	−140.8	20.17	0.9152	0	0.0679	0.0168
21	0.115	−194.6	35.04	0.0023	0.0335	0.6782	0.2860
22	0.6	250.7	6.0	0.3756	0.0196	0.4287	0.1761
23	22.0	−124.7	20.17	0.9152	0	0.0679	0.0168
24	0.115	−194.6	35.04	0.0023	0.0335	0.6782	0.2860
25	0.115	−172.8	35.04	0.0023	0.0335	0.6782	0.2860
26	0.115	11.00	35.04	0.0023	0.0335	0.6782	0.2860
27	22.0	17.16	4.79	0.8348	0	0.1228	0.0424
28	22.0	−3.17	20.17	0.9153	0	0.0679	0.0168

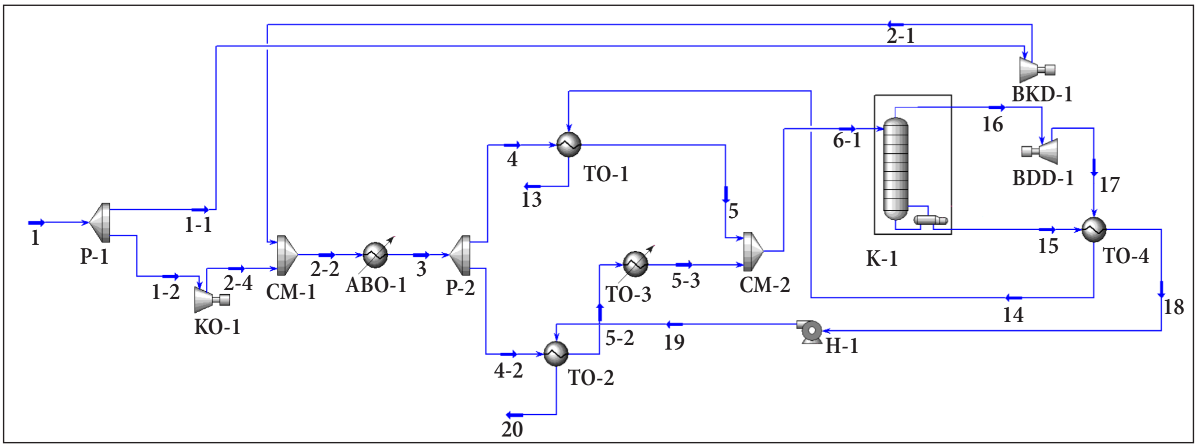

Fig. 3. The scheme of low-temperature gas separation with the rectification column without a condenser

of the low-temperature gas separation facility is shown in Fig. 3.

The amount of products obtained by the facility is equal to 5.242 kg/hour of the product No. 1 with methane content of 99.9% (CH_4 – 99.9%, H_2 – 0%, CO – 0.09%, N_2 – 0.01%) and 54.76 kg/hour of the product No. 2 with a low content of methane (CH_4 – 36.49%, H_2 – 19.69%, CO – 31.06%, N_2 – 12.76%). If the scheme shown in Fig. 3 is implemented, the product will be released as a pure methane in compressed shape.

To accomplish energy assessment of the expedience of application of the low-temperature gas separation technology realized on the scheme with the rectification column without a condenser, comparative calculations for approximate productivity of municipal solid wastes recycling equal to 1.6 ton/day (66.8 kg/hour, 529 ton/year) were made.

During realization of the proposed scheme the following products may be obtained: liquefied or gaseous methane under pressure equal to 25 MPa – 16.8 kg/day; fuel gas – 37.1 kg/hour; slag – 6.68 kg/hour.

A lower heating value of the fuel is an additive function defined as the sum of heating values of combustive components of fuel [27]. The values

Table 2. **Evaluation of generated energy amount**

Parameters	Values
Raw materials amount, kg/h	66.80
Raw materials amount, ton/day	1.60
Raw materials amount, ton/year	529
Products amount per hour:	
methane liquefied, kg/hour	16.80
fuel gas for heating, kg/hour	37.10
slag, kg/hour	6.68
Products amount per year (330 operative days):	
methane liquefied, ton/year	133.06
fuel gas for heating, ton/year	293.83
Lower heating value of syngas, kJ/m^3	9 467
Density, kg/m^3	0.827
Lower heating value of syngas, kJ/kg	7 829
Lower heating value of syngas, kWh/kg	2.17
Steam generator efficiency	0.9
Heat energy, kWh	72.62
Heat energy, kWh/year	575 123
Steam cycle efficiency	0.32
Electrical energy in steam cycle, kWh/year	184 039
Gas turbine cycle efficiency	0.45
Electrical energy in gas-turbine cycle, kWh/year	258 805
Slag, ton/year	52.91
Products amount, ton per 1 ton of raw materials:	
methane liquefied, ton per 1 ton	0.25
fuel gas for heating, ton per 1 ton	0.44
Heat energy, kWh/ton of raw materials	1087
Electrical energy in steam cycle, kWh/ton of raw materials	347.86
Electrical energy in gas-turbine cycle, kWh/ton of raw materials	489.18
Slag, ton per 1 ton of raw materials	0.10

of parameters on the amount of generated energy are shown in Table 2.

Calculation results show that a lower heating value of produced gas is equal to 9467 kJ/m^3.

Fuel gas is directed into the steam generator or combustion chamber, then it is sent to the electrical energy generation turbine. Two ways of electricity production were considered: the first one for the steam cycle, the second one for the direct fuel combustion using a gas turbine. When the steam cycle is applied, it is considered that the steam generator efficiency is equal to 90%, and steam cycle efficiency is equal to 32%. The obtained amount of electrical energy is equal to:

$$E_{El.En.} = q_{FG} \cdot \eta_{SF} \cdot \eta_{SC}, \tag{5}$$

where q_{FG} is lower heating value of the fuel gas; η_{SG} is steam generator efficiency; η_{SC} is steam cycle efficiency.

When electrical energy is generated at the gas-turbine equipment, it is considered that heat energy losses are equal to 10%, and gas-turbine equipment efficiency is equal to 50%.

The obtained amount of electrical energy is equal to:

$$E_{El.En.} = 0.9 \cdot q_{FG} \cdot \eta_{GTC}, \tag{6}$$

where η_{GTC} is gas-turbine cycle efficiency.

Calculation results prove that the amount of electrical energy generated on proposed technology using 1 ton of raw materials is equal to 348 kWh and 489 kWh in steam and gas-turbine cycles, correspondingly.

CONCLUSIONS

1. The results of numerical simulations show that implementation of the facility of low-temperature separation of multicomponent hydrocarbon mixtures provides formation of flows of energy resources. The amount of products obtained by the facility is equal to 5.242 kg/h of the product No. 1 with methane content of 99.98% and 54.76 kg/h of the product No. 2 with low content of methane.

2. The use of waste utilization technology, which includes the stage of low-temperature separation of the resulting gas mixtures, allows to compensate daily and seasonal irregularities of electrical energy and heat consumption by means of manufacturing fuel products suitable for storage and subsequent realization.

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ATLIEKŲ UTILIZAVIMO TECHNOLOGIJOS, PAPILDOMAI NAUDOJANČIOS ŽEMATEMPERATŪRINĮ SUSIDARIUSIŲ DUJŲ ATSKYRIMĄ, ENERGETINIO EFEKTYVUMO TYRIMAS

Santrauka

Pasaulyje egzistuoja aukštos temperatūros atliekų utilizavimo technologijos, kurios naudoja gautas generatorines dujas kaip kurą naujai įvestoms atliekoms perdirbti / neutralizuoti. Tačiau atliekų struktūra nėra pastovi, tad susidariusių generatorinių dujų sudėtis ir kokybė taip pat labai skiriasi. Gali būti prarandama dalis generatorinių dujų, kurios būtų panaudotos procese. Straipsnio tikslas yra pateikti aukštos temperatūros atliekų utilizavimo technologijos energijos vartojimo efektyvumo tyrimą, apimantį dujinių mišinių atskyrimą žemoje temperatūroje (žemos temperatūros separaciją). Modeliuojant buvo atlikta daugiakomponentinių angliavandenilių mišinių atskyrimo technologinio įrenginio veikimo analizė ir tolesnė jo parametrų optimizacija, siekiant pagerinti jo efektyvumą ir sumažinti energijos sąnaudas, susijusias su dujinimo atliekomis. Šiam tikslui buvo naudojami klasikiniai termodinamikos modeliai ir dėsniai, įskaitant Peng-Robinsono būsenos lygtį, apibūdinančią šiluminių-fizikinių charakteristikų koeficientus. Daugiakomponentinių sistemų (su trimis ir daugiau komponentais) skaičiavimo sudėtingumas neleidžia taikyti būsenos diagramų. Taigi fizikinių charakteristikų modeliavimui buvo naudojama REFPROP programa. Iš modeliavimo rezultatų matyti tokios utilizavimo technologijos ekonominis efektyvumas: gautų produktų kiekis yra 5,242 kg/val. kuro produkte Nr. 1, kurio metano kiekis yra 99,98 % ir 54,76 kg/h, ir kuro produkte Nr. 2, kuriame yra mažas metano kiekis.

Raktažodžiai: atliekos, atliekų panaudojimas, generatorinės (sintetinės) dujos, energijos charakteristikos