SOLID WASTES CONVERSION INTO ELECTRIC AND THERMAL ENERGY USING A GASIFIER AND AN ELECTROCHEMICAL GENERATOR

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ABSTRACT

In Russia, 3.4 billion tons of municipal solid wastes (SW) are accumulated annually. Over 40 thousand hectares of fertile lands have been used for solid waste disposal; and the areas to be disposed each year for the SW landfills amount to as much as three thousand hectares. This work presents calculation results are reported from the study of a power plant based on the solid oxide fuel cells (SOFCs), which utilizes as fuel the synthesis gas generated through the SW steam gasification in an autothermal gasifier. Solid oxide fuel cells (SOFCs) are the most convenient for such a combined system, as due to high operating temperatures they do not require high fuel quality. The calculations have demonstrated the following: the temperature in the reaction vessel of the gasifier is at 1,000°C, the synthesis gas output is 55 m^3/h, the chemical efficiency is 35.4%, and the synthesis gas combustion heat is 1.6352 kJ/kg of synthesis gas. The electric power electrochemical generator is 97.86 kW, the (total) electric efficiency of electrochemical generator is 39.1%, the temperature of gases effluent from the boiler-utilizer is at 630°C. Theorized the possibility of solid waste into electrical and thermal energy with full efficiency more than 79%.

Keywords: autothermal steam gasification, domestic solid wastes, electrochemical generator, hydrogen fraction, EMF, (total) efficiency, temperature, stoichiometry, solid oxide fuel cells (SOFC), power, heat.

1 INTRODUCTION

In Russia, 3.4 billion tons of municipal solid wastes (SW) are accumulated annually. Over 40 thousand hectares of fertile lands have been used for solid waste disposal; and the areas to be disposed each year for the SW landfills amount to as much as three thousand hectares.

SW to be dumped into the landfills comprise (percent by weight): paper and cardboard (30%); plastic (5%); textile (6%); rubber and skin (3%); wood (4%); food waste (22%); other (30%). One household would routinely generate 225 kg of SW to be dumped in the landfills each year.

Solid wastes are commonly known to be divided into medical, biological, constructional, transport-related, agricultural, and industrial wastes.

To utilize medical and biological wastes, incinerators are known to be used. They may reach 270 kg/h in capacity; and due to a high temperature (1,000°C), toxic and pathogenic agents are eliminated. As of today, SW utilization in Russia to yield energy is used to one per cent of the possible capacity only. As a rule, 96.5% of SW is disposed in the landfills, which are prone to be bleeding gaseous products containing carbon oxide, ammonium, and hydrogen sulfide. In this paper, calculations are reported from the research on the SW converting into electric and thermal energy using a solid oxide fuel cell-based electrochemical generator and an auto thermal gasifier for carrying out SW steam reforming.

Solid oxide fuel cells (SOFCs) appear to be most convenient for the purpose, because they use air as oxidant and the synthesis gas, resulted from SW steam reforming, as fuel. Solid oxide fuel cells (SOFCs) are the most convenient for such a combined system, as due to high operating temperatures they do not require high fuel quality [1]. The electrochemical generator uses SOFCs of flat plane design with the direct flow of fuel and oxidant, with the

catalysts made of NiYSZ in the anode, cathode and electrolyte between them of $(ZrO_2)_{0.9}$ $(SC_2O)_{0.1}$ [2]. In recent years, actively developed new methods of solid waste management using modern solid electrochemical generators in combination with Stirling engines and gas turbines [3]–[5].

The study [6], offers over 220 versions of calculated SOFCs according to two arrangements: one involving anode gases recirculation and the other without it. A conclusion is made that so much the simpler the arrangement, so much the better.

A technique that we have developed allows predicting for the process parameters: the temperature in the reaction vessel of auto thermal gasifier for SW converting into synthesis gas; the temperature at the SOFC anode; the (total) electric efficiency of the electrochemical generator (ECG); the fraction of hydrogen oxidized on the anode; the specific consumption rates of SW for producing electric and thermal energies; the losses in the ECG with effluent gases and into the environment.

2 SCHEMATIC OF GASIFIER AND ECG-BASED HEAT AND POWER PLANT

Fig. 1. A schematic of the gasifier and ECG-based HPP for converting solid wastes (SW) into electric and thermal energy:

1 - gasifier; 2 - cyclone for synthesis gas; 3 - cyclone for synthesis gas combustion products; 4 - mechanical filter for synthesis gas; 5-synthesis gas cooler; 6 - synthesis gas scrubber; 7 - mechanical filter for synthesis gas combustion products; 8 - synthesis gas heater; 9 - synthesis gas combustion products utilizer; 10- flat plate SOFC-based ECG; 11- boiler-utilizer; 12 - network heater. I - TDW input; II - air inlet; III - chemically cleaned deaired water inlet; IV - effluent gases outlet; V - electric energy output; VI - ashes removal.

The synthesis gas was produced using a fluidized-bed gasifier with a layer of fused alumina of 0.32 mm-sized particles to auto thermal oxygen-free steam reforming of SW (1). Fig. 2 displays a detailed description of such gasifier.
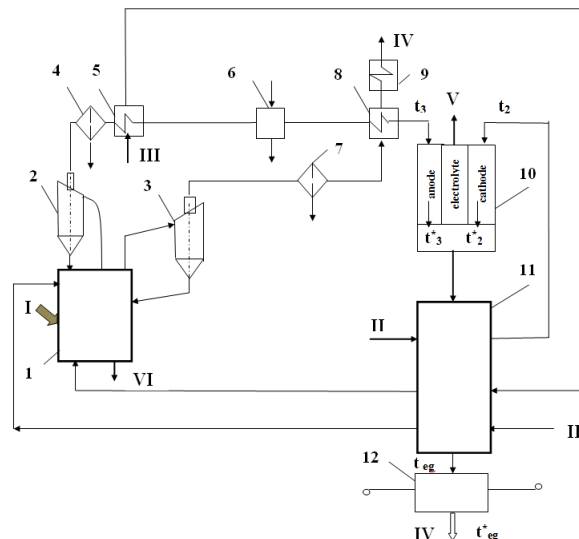

Figure 1: The HPP schematic.

Superheated steam from the BU is fed into a cap steam distribution grate of the gasifier. To ensure the auto thermal process and to provide heating of the gasification products up to 1,000°C, which eliminates toxic and pathogenic agents, a combustion chamber is designed, where synthesis gas gets partially oxidized. The thermal power thus generated is transferred into the reaction vessel through intermixing the dispersed particles of fused alumina; with synthesis gas being removed via the central pipe separately from the consumption products. Domestic solid wastes are fed in the same direction with the air, similar to the way it is done in the downdraft gasification system, when dry-run products are passing the burning zone and decompose, which makes it possible to eliminate 94% of phenols, toxins, and pathogens [7]. In the fluidized-bed, the solid phase (fused alumina) mixes well, unlike the gaseous phase which mixes poorly. Therefore, to ensure better mixing of the synthesis gas and air, a peak 11 is provided (see Fig. 2). Thus, a uniform temperature is maintained throughout the entire fluidized bed.

Fig. 2, Gasifier system for auto thermal steam gasification of domestic solid wastes (SW). 1 - cap steam distribution grate; 2 - boiler; 3-fluidized bed of fused alumina; 4 - thermal insulation; 5 - lock feeder; 6 - gate valve; 7 - SW hopper; 8 - central pipe for removing synthesis gas; 9 - connecting pipe for removing completely burnt synthesis gas combustion products;10 - pipe for ash removal; 11 - peak; 12 - wide-mesh screen; 13 - Connecting pipe for air inlet. I - SW feed; II - air inlet; III - steam inlet; IV- synthesis gas combustion products outlet; V- synthesis gas output; VI –ash removal.

To trap the entrained particles of fused alumina and to return them back to the bed, the cyclones (2) and (3) are installed and the mechanical filters (4) and (7) are provided. The entrained particles of fused alumina are returned to the bed as the SW are fed into the lock feeder.
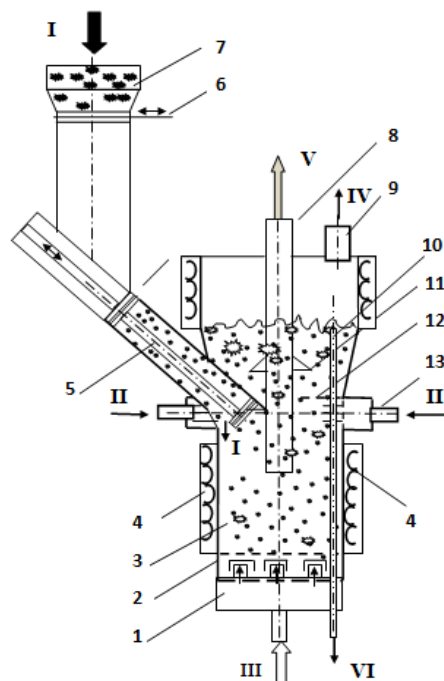

Figure 2: Gasifier system for auto thermal steam gasification of domestic solid wastes (SW).

Synthesis gas at the outlet of the gasifier (see Fig. 1) is cooled down in the heat exchanger (5), is purified in the scrubber (6), is heated in the heater (8), and is fed into the anode channel of the electrochemical generator. Thermal power of the gases effluent from the ECG is used in the boiler-utilizer (10) to produce steam and to heat air. The combustion products-generated power underused in the boiler-utilizer is used in the network heater (12). The combustion products-generated power underused in the gasifier is used in the heater (9) to heat water for household purposes. The synthesis gas is cleaned off the sulfur dioxide using alkali and off hydrogen sulfide using sodium carbonate in the scrubber (6) [8] and using an activated carbon filter. The synthesis gas is heated up to 750 °C using the heater (8) working on the synthesis gas combustibles. The electrochemical generator is based on the SOFC (10); and the boiler-utilizer (11) is designed for heating up the cathode air, the air for gasifier, and for producing steam for the gasifier. The network heater (12) is designed for heating water for household needs.

3 GASIFIER PROCESSES SIMULATION

For steam gasification, the SW of the following composition are used (percent by mass): C^r (17.4); H^r (0.88); O^r (13.85); N^r (0.55); S^r (0.11); A^r (31.9); W^r (33.95). The SW combustion heat is Q^p_l=5,000 kJ/kg.

In the reaction vessel, a reaction of carbon (SW) with steam is carried out at a molar ratio of carbon to water as C:H_2O=1:1 according to the stoichiometric equation

$$C+H_2O=0.88H_2+0.88CO+0.09CO_2+0.06H_2O+0.0293CH_4, \qquad (1)$$
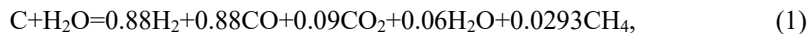
with the endothermal effect q_{x2}=2,900 kJ/kg (of synthesis gas). The synthesis gas composition is (percent by volume): H_2 (45.378); CO (45.378); CO_2 (4.64); H_2O (3.094); CH_4 (1.51).

True mass isobaric specific heat capacity of synthesis gas is C_{SG}=2.19 kJ/(K kg of synthesis gas). In the combustion chamber, a reaction of partial oxidation of the synthesis gas is carried out, with the air ratio of 1.2 according to the stoichiometric equation

$$0.88H_2+0.88CO+0.09CO_2+0.06H_2O+0.0293CH_4+1.2(O_2+3.76N_2)=H_2O+CO_2+0.2O_2+4.512N_2. \ (2)$$
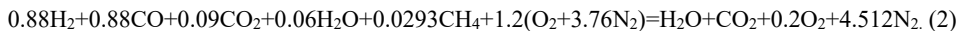
The combustion heat of wet synthesis gas is q_{x1}=-16,352 kJ/(kg of synthesis gas). The synthesis gas combustion products are of the following composition (percent by volume): H_2O (14.9); CO_2 (14.9); O_2 (2.97); N_2 (67.23). The true mass isobaric specific heat capacity of the combustion products is C_c =10.42 kJ/(K kg of synthesis gas).

To produce electric power in the ECG at a HPP of Q_e=100 kW, production of synthesis gas would be required in a gasifier with a combustion heat of q_{x1}= 16.352 kJ/kg at a total efficiency of η =0.4 (40%) as taken from [9], [10]:

$$B_{SG} = Q_e/q_{x1} \cdot \eta = 100/(16.352 \cdot 0.4) = 15.29 \cdot 10^{-3} \text{ kg/s}.$$

3.1 Gasifier thermal balance equation

The combustion heat of the part of synthesis gas $(1-x) \cdot q_{x1}(1-\sum_3^6 q_i)$ introduced with dry SW q7 , moisture q8, air q9, and steam q10 $(\sum_7^{10} q_i)$, is spent for carrying out the endothermal reaction producing a fraction x of the synthesis gas through the SW carbon steam reforming $x \cdot q_{x2}$, for heating the reaction products $x \cdot C_{SG} \cdot t$, for heating the

combustion products of the part of the synthesis gas $(1 - x) \cdot C_c \cdot t$, and for heating, evaporating, and superheating the steam from the wet SW q_{11}.

$$(1 - x) \cdot q_{x1}(1 - \Sigma_3^6 q_i) + \Sigma_7^{10} q_i = x \cdot q_{x2} B_{SG} + x \cdot C_{SG} \cdot t + (1 - x) \cdot C_c \cdot t + q_{11}, \quad (3)$$

where $\Sigma_3^6 q_i = q_3 + q_4 + q_5 + q_6$ is the sum of heat losses in the gasifier due to chemical and/or mechanical under burning, losses into the environment through the thermal insulation and with the ashes, kJ/kJ.

$$\sum_3^6 q_i = 0.2 \text{ (assumed)};$$
$$\Sigma_7^{10} q_i = q_7 + q_8 + q_9 + q_{10},$$

where

$$q_7 = (12C_{dsw}t_l)/(C^r 30) == (12 \cdot 2.5 \cdot 20)/(0.174 \cdot 30) = 115 \text{ kJ/kg}.$$

12 and 30 are the molecular mass of carbon and synthesis gas in eqn (1), C_{SW} is the specific heat capacity of SW, t_l is temperature 20°C, C^r is relative carbon content, kg/kg in SW (per working mass);

$$q_8 = (12W^r 4.19 \, t_l)/(C^r 30) = = (0.3395 \cdot 12 \cdot 4.19 \cdot 20)/(0.174 \cdot 30) = 65 \text{ kJ/kg}),$$

where W^r is the moisture of SW, kg/kg;

$$q_9 = (164.736 C_a t_1)/30 = = (164.736 \cdot 1.024 \cdot 200)/30 = 1{,}098 \text{ kJ/(kg)},$$

where 164.736 is the molecular mass of air in the Eq. (2), t_1= 200°C is the heating temperature of air in the boiler-utilizer (assumed); $C_a = 1.024 \text{ kJ/K} \cdot \text{kg}$ is the true isobaric specific heat capacity of air.

$$q_{10} = (18C_s \cdot t_1)/30 = = (18 \cdot 1.977 \cdot 200)/30 = 236 \text{ kJ/kg},$$

where C_s is the true isobaric specific heat capacity of steam.
The sum $\Sigma_7^{10} q_i = 1{,}514 \text{ kJ/(kg of synthesis gas)}$.

$$q_{11} = (W^r 12 h_{SS})/(C^r 30) = 0.3395 \cdot 12 \cdot 2{,}874/(0.174 \cdot 30) = 2{,}243 \text{ kJ/kg},$$

where h_{SS} is the superheated steam enthalpy.
From eqn (3) the fraction x is expressed as a function of temperature t in the reaction vessel of the gasifier:

$$x = \frac{q_{x1}(1 - \Sigma_3^6 q_i) + \Sigma_7^{11} q_i - C_{SW} \cdot t - q_{11})}{q_{x1}(1 - \Sigma_3^6 q_i) + q_{x2} + C_{SG} \cdot t - C_c \cdot t}. \quad (4)$$

Substituting into eqn. (4) the temperature t= 1,000°C gives the value of the useful fraction of synthesis gas output from the gasifier as x=0.249, and the fraction $(1-x)$ =0.751 is spent for maintaining the auto thermal gasification of SW steam reforming.

Therefore, to produce B_{SG}=15.29·10^{-3} kg/s of synthesis gas, the feedstock to be put in the gasifier should be as follows:

SW - G_{SW}=141.1·10^{-3} kg/s;

steam - G_{H2O} =36.84·10^{-3} kg/s;
air - G^{**}_a =253.23·10^{-3} kg /s.
Total: 431.17·10^{-3} kg/s (as defined from eqn (1)).
The following must be taken out from the gasifier:
combustion products G_c =314·10^{-3} kg/c (as defined from eqn (2));
synthesis gas B_{SG} =15.29·10^{-3} kg/s;
ashes G_{ash} =45·10^{-3} kg/s;
moisture from the SW G_{WW} =47.9·10^{-3} kg/s;
oxygen from the SW G_{O2} =19.54·10^{-3} kg/s;
other products G_{op} =4.32·10^{-3} kg/s.
Total: 431.17·10^{-3} kg/s.

3.2 Chemical efficiency of gasifier

$$\eta_x = (B_{SG} \cdot q_{x1})/(G_{SW} \cdot Q_l^p) \ . \tag{5}$$

To implement this project, a gasifier is required to have the following dimensions. The retort neck diameter is 1 m; the widest retort diameter is 1.62 m; the central pipe (for synthesis gas output) diameter is 0.5 m; the fluidized bed height is 1m. The calculations were performed for the working velocity of gasification products of 0.5 m/s at actual parameters of fused alumina particles size of 0.32 mm.

3.3 Determining (total) efficiency of ECG

Fuel cells would normally operate at isobaric-isothermal parameters. The work performed in an isobaric-isothermal process equals the decrease in the Gibbs Free Energy [12]; and the electric power equals the decrease in the Gibbs Free Energy ΔG kJ/kg of synthesis gas at 1,006 K, multiplied by the synthesis gas consumption rate B_{SG}, kg/s:

$$Q_e = \Delta G \cdot B_{SG} \ . \tag{6}$$

On the other hand, the electric power [8], is

$$Q_e = B_{SG} \cdot q_{x1} \cdot \eta \ . \tag{7}$$

Thus, by equating the two expressions, we then get the (total) electric efficiency $\eta = 0.391(39.1\%)$. Because the value of η turns out to be less than the previously set value 0.4, then the resulted electric power has to be somewhat less than 100 kW.

4 BOILER-UTILIZER

The boiler-utilizer serves as the site, where hydrogen, fed from the anode channel and underoxidized in the anode, can burn down releasing the power $B_{SG} \cdot (1 - \varphi_\text{т}) \cdot \Delta H_1^0$, and carbon monoxide and methane are burned releasing the power $B_{sg} \cdot \Delta H_2^0$, reacting with oxygen-depleted air $0.56 O_2 + 3.76 \ N_2$ coming from the cathode channel, according to the following stoichiometric equation:

$$0.88 CO + 0.09 CO_2 + 0.94 H_2O + 0.0293 CH_4 + (0.56 O_2 + 3.76 N_2) = CO_2 + H_2O + 3.76 N_2. \tag{8}$$
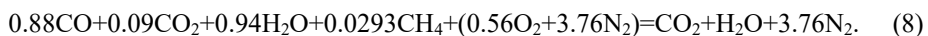
The exothermic effect of this reaction is $\Delta H_2^0 = 9{,}192$, kJ/kg of synthesis gas.

The numbers included in eqns (1)–(7) values are given in Table 1.

4.1 Boiler-utilizer power budget

The power $B_{sg}^* \cdot C_{sg}^* \cdot t_3^*$ coming in with the products from the anode channel, the power $G_a \cdot C_a^{**} \cdot t_2$ fed with the air from the cathode channel, the power $B_{sg} \cdot (1 - \varphi_\text{т}) \cdot \Delta H_1^0$ released as a result of oxidation of hydrogen unoxidized in the anode, the power $B_{sg} \cdot \Delta H_2^0$ resulted from oxidation of carbon monoxide and methane coming from the anode channel, the power $G_a \cdot C_a \cdot t_a$ resulted from the air fed into the cathode channel, the power $C_a \cdot G_a^{**} \cdot t_a$, from the air for gasifier, and the power $G_{H2O} \cdot h_{ek}$ of the feed water for the gasifier, - all is spent for generating steam for the gasifier $G_{H2O} \cdot h_{пп}$, for heating the cathode air $G_a \cdot C_a^{**} \cdot t_2$, for heating the air for the gasifier $G_a^{**} \cdot C_a^{***} \cdot t_1$ and for heating the gasses effluent from the BU $G_{eg} \cdot C_{eg} \cdot t_{eg}$. The value of $\varphi_\text{т}$ obtained previously in [11]–[13].

$$B_{sg}^* C_{sg}^* t_3^* + G_a^* C_a^* t_2^* + B_{sg}(1 - \varphi_\text{т})\,\Delta H_1^0 + B_{sg}\Delta H_2^0 + + G_a C_a t_a + C_a G_a^{**} t_a + G_{H2O} h_{эк} =$$
$$= G_{H2O} h_{пп} + G_a C_a^{**} t_2 + G_a^{**} C_a^{***} t_1 + G_{eg} C_{eg} t_{eg}. \tag{9}$$

From eqn (9), the temperature of gasses effluent from the BU can be written down:

$$\begin{aligned} t_{eg} = [B_{sg}^* C_{sg}^* t_3^* + G_a^* C_a^* t_2 + B_{sg}(1 - \varphi_\text{т})\,\Delta H_1^0 + B_{sg}\Delta H_2^0 \\ - G_a(\,G_a^{**} t_2 - C_a t_a) - \\ - G_a^{**}(C_a^{***} t_1 - C_a t_a) - G_{H2O}(h_{ss} - h_{eк})]/(G_{eg} C_{eg})\,. \end{aligned} \tag{10}$$

Substituting the values from Table 2 into eqn (9) yields the value $t_{eg} = 630\,^{\circ}\text{C}$. Power out of the BU is

$$Q_2 = G_{eg} \cdot C_{eg} \cdot t_{eg}\,. \tag{11}$$

Power of the network heater ($t_{eg}^* = 120\,^{\circ}\text{C}$ into the flue)

$$Q_{NH} = G_{eg} \cdot C_{eg} \cdot (t_{eg} - t_{eg}^*)\,. \tag{12}$$

The specific ECG heat loss with effluent gases is

$$q_2 = Q_2/(\,B_{sg} \cdot q_{x1})\,. \tag{13}$$

The specific ECG heat loss into the environment is

$$q_5 = 1 - \eta - q_2 = 0.32. \tag{14}$$

The chemical underburning is assumed to be $q_3 = 0$.

The synthesis gas heater power is (position 8 in Fig.1)

$$Q_{sg} = G_{sg}(C_{sg} \cdot t_3 - C_{sg}^{**} \cdot t_l)\,. \tag{15}$$

Table 1:　Settings in the heat balance equation for electrochemical power plant parts (1)–(7).

Symbol	B_{sg}	B^*_{sg}	C_{sg}	C^*_{sg}	C^*_a	C^{**}_a	G_a	G^*_a	t_2	t^*_2	t_3	t^*_3	ΔH^o_1	Q_e
Unit	kg/s	kg/s	kJ/K kg	kJ/K kg	kJ/K kg	kJ/K kg	kg/s	kg/s	°C	°C	°C	°C	kJ/kg	kW
Value	$15.29{\cdot}10^{-3}$	$22.47{\cdot}10^{-3}$	2.15	1.621	1.14	1.115	$69.97{\cdot}10^{-3}$	$62.97{\cdot}10^{-3}$	600	633	700	733	7,160	97.86

Table 2:　Settings included in the equation of thermal balance of the boiler-utilizer (10).

Symbol	B_{sg}	B^*_{sg}	C^*_{sg}	C^*_a	C_a	C^{**}_a	C^{***}_a	C_{yx}	G_a	G^*_a	G^{**}_a	G_{H2O}	G_{eg}	t_1	t_a	t_2	t^*_2	t_3	t^*_3	h_{ec}	h_{ss}	ΔH^o_1	ΔH^o_2
Unit	kg/s	kg/s	kJ/K kg	kJ/K kg	kJ/K kg	kJ/K kg	kJ/K kg	kJ/K kg	kg/s	kg/s	kg/s	kg/s	kg/s	°C	°C	°C	°C	°C	°C	kJ/kg	kJ/kg	kJ/kg	kJ/kg
Value	$15.29{\cdot}10^{-3}$	$22.47{\cdot}10^{-3}$	1.621	1.14	1.05	1.115	1.024	1.35	$69.97{\cdot}10^{-3}$	$62.97{\cdot}10^{-3}$	$253.23{\cdot}10^{-3}$	$36.84{\cdot}10^{-3}$	$85.26{\cdot}10^{-3}$	20	20	600	633	700	733	1,276	2,874	7,160	9,192

The temperature of combustion products behind the synthesis gas heater is

$$t_x = t - Q_{sg}/(G_c \cdot C_c). \tag{16}$$

The power of utilizer (position 12 in Fig. 1) of combustion products heat behind the synthesis gas heater is

$$Q_{NH}^* = G_c \cdot C_c(t_x - t_{eg}^*). \tag{17}$$

The fuel utilization is

$$\eta_u = (Q_e + Q_{NH} + Q_{NH}^*)/(G_{dsw} \cdot Q_l^P). \tag{18}$$

5 SOFC-BASED MINI-HPP PERFORMANCE CHARACTERISTICS

The capability of dividing the SW consumed for electric power or heat generation. Absolute SW consumption for generation of electric energy

$$G_{ldsw} = Q_e \cdot 1 \cdot 3{,}600/(Q_l^p \cdot \eta_u). \tag{19}$$

Specific SW consumption for generation of electric energy

$$b_e = G_{hdsw}/Q_e. \tag{20}$$

Absolute SW consumption for heat generation

$$G_{hdsw} = [(Q_{NH} + Q_{NH}^*) \cdot 1 \cdot 3{,}600]/(Q_l^p \cdot \eta_u). \tag{21}$$

Specific SW consumption for heat generation

$$b_h = G_{hdsw} \cdot 10^6/[(Q_{NH} + Q_{NH}^*) \cdot 1 \cdot 3{,}600]. \tag{22}$$

The difference between SW consumption to be fed into the gasifier and the one used for generation of electric and thermal energies is

$$\Delta G_{dsw} = G_{dsw} - (G_{ldsw} + G_{hdsw})/3{,}600 \tag{23}$$
$$(\Delta G_{dsw} \text{ -is zero}).$$

The calculation results are presented in Table 3.

6 CONCLUSIONS

1. A calculation research effort has been made to support the application of an auto thermal fused-alumina fluidized-bed gasifier for synthesis gas generation through the steam gasification of domestic solid wastes, which is to be used for SOFC-based electrochemical generator operation.
2. The calculations have demonstrated the following: the temperature in the reaction vessel of the gasifier is at 1,000°C, the synthesis gas output is 55 m3/h, the chemical efficiency is 35.4%, and the synthesis gas combustion heat is 1.6352 kJ/kg of synthesis gas.
3. The ECG electric power is 97.86 kW, the ECG efficiency is 39.1%, the temperature of gases effluent from the boiler-utilizer is at 630°C.

Table 3: Nominal characteristics calculated for the domestic solid waste processing plant.

Characteristic	Symbol	Unit	Eqn. No.	Calculation	Value
Useful fraction of synthesis gas output from gasifier	x	-	(4)	$\dfrac{16{,}352(1-0.2)+1{,}514-10.42\cdot1{,}000}{16{,}352(1-0.2)+2{,}900+2.19\cdot1{,}000-10}$	0.249
Chemical Efficiency of gasifier	η_x	%	(5)	$15.25\cdot10^{-3}\cdot16{,}352\cdot100/141.1\cdot10^{-3}\cdot5{,}0$	35.4
ECG electric power	Q_e	kW	(6)	$192{,}000\cdot15.29\cdot10^{-3}/30$	97.86
ECG (total) electric efficiency	η	(%)	(7)	$97.86\cdot10^2/(15.29\cdot10^{-3}\cdot1{,}6352)$	39.14
Temperature of gases effluent from the boiler-utilizer	t_{eg}	°C	(10)	$[22.47\cdot10^{-3}\cdot1.621\cdot733+62.79\cdot10^{-3}\cdot1.115\cdot600+(1-0.9)\cdot7{,}160\cdot15.29\cdot10^{-3} + {}$ $+9{,}122\cdot15.29\cdot10^{-3}\cdot69.97\cdot10^{-3}\cdot(1.115\cdot600-1.005\cdot20)-253.23\cdot10^{-3}\cdot1.005\cdot20)-36.84\cdot10^{-3}\cdot(2{,}874-1{,}276)](85.26\cdot10^{-3}\cdot1.35)$	630
Power of gases effluent from the boiler-utilizer	Q_2	kW	(11)	$85.26\cdot10^{-3}\cdot1.35\cdot630$	72.51
Power of network heater	Q_{NH}	kW	(12)	$85.26\cdot10^{-3}\cdot1.35\cdot(630-120)$	58.7
Specific heat loss with gases effluent from the boiler-utilizer	q_2	kW/kW	(13)	$72.51/(15.29\cdot10^{-3}\cdot16{,}352)$	0.289
Specific heat loss into environment	q_5	kW/kW	(14)	$1-0.3914-0.289$	0.32
Power of synthesis gas heater	Q_{sg}	kW	(15)	$15.29\cdot10^{-3}\cdot(2.15\cdot600-1.89\cdot20)$	22.4
Temperature of combustion products behind the synthesis gas heater	t_x	°C	(16)	$1{,}000-22.4/(314\cdot10^{-3}\cdot1.708)$	878
Power of utilizer of combustion products heat behind the synthesis gas heater	Q^*_{NH}	kW	(17)	$314\cdot10^{-3}\cdot1.708(878-120)$	406
Fuel (SW) utilization	η_U	Non-dimentional	(18)	$(97.86+58.7+406)/(141.1\cdot10^{-3}\cdot5{,}000)$	0.797

Table 3: Continued.

Characteristic	Symbol	Unit	Eqn. No.	Calculation	Value
Absolute SW consumption for generation of electric energy	G_{lSW}	kg/h	(19)	$97.86 \cdot 1 \cdot 3{,}600/(5{,}000 \cdot 0.797)$	88.4
Specific SW consumption for generation of electric energy	b_e	kg/ kW·h kg eq.f./ kW·h	(20)	$88.4/97.86$ $0.9 \cdot 5{,}000/29{,}330$	0.9 0.153
Absolute SW consumption for heat generation	G_{hSW}	kg/h	(21)	$(58.7 + 406) \cdot 1 \cdot 3{,}600/(5{,}000 \cdot 0.797)$	420
Specific SW consumption for heat generation	b_h	kg/GJ kg eq.f./GJ kg eq.f./GC	(22)	$420 \cdot 10^6/(58.7 + 406) \cdot 1 \cdot 3{,}600$ $251 \cdot 5{,}000/29{,}330$ $42.8 \cdot 4.19$	251 42.8 179
Difference between SW consumption to be fed into the gasifier and the one used for generation of electric and thermal energies	$\Box G_{SW}$	kg/s	(23)	$141.1 \cdot 10^{-3} - (88.4 + 420)/3{,}600$	0

4. The specific SW consumption to produce electric energy is 0.9 kg/kWh (0.153 kg eq.f./kWh), and to produce thermal energy is 251 kg/GJ (43.8 kg eq.f./GJ;179 kg eq.f./GC).
5. Theorized the possibility of solid waste into electrical and thermal energy with full efficiency more than 79%.

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