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Water, Wastewater and Energy in Smart Cities

Evaluation of selected sewage sludge gasification technological parameters

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Abstract. Evaluation of selected sewage sludge gasification technological parameters was shown in this paper. Degree of carbon conducted in combustible substance and syngas efficiency (technological readiness coefficient) in accordance with equations were calculated. Enthalpy of individual compounds formation and energy balance were calculated in accordance with rule of Hess.

1 Introduction

One of the main materials, that are formed during the wastewater treatment and production are sewage sludge's. Physical parameters like size of particles and composition of them depends on wastewater treatment conditions [1]. Methods of sewage sludge management should ensure sanitary safety. Disposal solutions of hazardous substances included in sludge's are available by thermal processes like gasification. Combustible gas (syngas) arises after cycle of the reactions between fuel and gasification agent is one of the main products of this process. Technological parameters like: syngas lower heating value, degree of combustible substance conversion and syngas chemical efficiency(technological readiness coefficient) for evaluation of efficiency of the process can be used. In range of temperatures over than 700°C for sewage sludge air gasification, fuel conversion degree is in the range 65-72% and range of syngas efficiency is from 30 to 50% what was shown by authors [2]. However, if temperature range increase from 600 to 900°C the chemical efficiency of gasification process will increase to 47,5%, what has been proved by [3]. The lower heating value of produced syngas achieved by authors was 4,19 MJ/m^3. Sewage sludge may be used for co-gasification process. Then fuel used in gasification is blended from different materials like sewage sludge with wood, biomass waste or coal. Fuel mixtures changes cause increases some technological parameters like syngas efficiency. Increase of this parameter is available by increase of sludge's to wood ratio in fuel mixture what has been found by the authors of [4]. Evaluation of selected technological parameters like: degree of carbon conversion contained in combustible substance and syngas chemical efficiency during sewage sludge air gasification was the aim of this paper.

2 Research material

Dried sewage sludge from municipal wastewater treatment plant in Bialystok was used in the experiment. Fuel properties were prepared in accordance with actual standards and regulations: humidity was determined in accordance with [5], combustible and incombustible parts concentration with [6],volatile matter [7], carbon and hydrogen concentration [8], nitrogen concentration [9], sulphur concentration [10], chlorine [11], higher heating value [12]. Samples were prepared in accordance with [13]. Results of the tests were shown in Table 1.

Table 1. Sewage sludge fuel properties

Parameter	**Value**
C % $_{\text{(dry mass)}}$	36.19
H % $_{\text{(dry mass)}}$	3.63
N % $_{\text{(dry mass)}}$	1.02
S % $_{\text{(dry mass)}}$	0.66
Cl % $_{\text{(dry mass)}}$	0.52
O % $_{\text{(dry mass)}}$	22.11
A % $_{\text{(dry mass)}}$	35.87
Volatile matter % $_{\text{(dry mass)}}$	49.2
Combustible matter % $_{\text{(dry mass)}}$	64.13
Moisture %	14.78
LHV MJ/kg $_{\text{(dry mass)}}$	14.68
HHV MJ/kg $_{\text{(dry mass)}}$	15.47

3 Experiment

Sewage sludge was air-gasified in 5 kW countercurrent gas generator. Gas composition was measured by GAS3100 syngas analyzer. Concentrations of combustible and incombustible gases like CO, CO_2, CH_4, H_2 i O_2 were measured. In the range 700-800°C was the temperature of the process. The measurement of this parameter was taken using nickel type K thermocouples linked with the control panel connected to the computer. The technological parameter of air fuel ratio was calculated in accordance with equation:

$$\Phi = \frac{G_{\text{fuel}}}{V_{\text{conv.}}} = \frac{1.260}{2.808} = 0.45 \tag{1}$$

Where: G_{fuel} – fuel stream (kg/h),V_{conv} –stream of gasification agent (air) (kg/h)
Description of sub processes areas of sludge air gasification in countercurrent pipeline gas generator shown in Fig.1 was prepared in accordance with [15,16] .

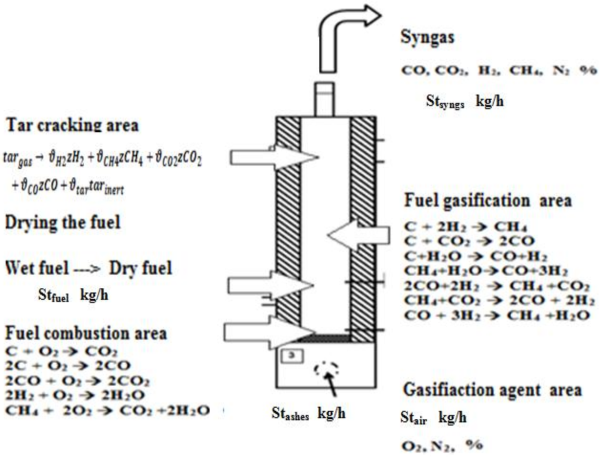

Fig. 1. Graphical concept of sewage sludge gasification in pipeline gas generator

Where: Stfuel – fuel stream [kg/h], Stsyngas – syngas stream [kg/h], ϑ – stoichiometric coefficients [-].

Gasification process consists of different sub processes where specific chemical reactions occurs [14]. Removing of fuel humidity starts at the beginning. Then in primary and secondary reactions gases like: methane, steam, carbon monoxide and also tars are formed. The last product is cracked in the cracking area in accordance with post processing tars [15]. Concentrations of syngas compounds formed in gasification were shown in Fig 2.

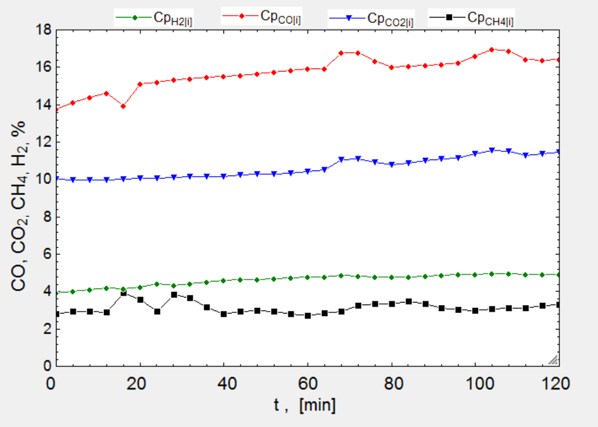

Fig. 2. Syngas composition in percent concentrations while steady state gas generator (without starting and quenching

Combustible gases concentrations like: CO, H_2 and CH_4 were in the ranges 14-17%, 4-5% and 3-4%. Small changes concentrations testify to stability of the process. Descriptions and experimental results of sewage sludge gasification were shown in [14].

4 Energy balance

Syngas lower heating value depends on combustible gases presence like: CO, H_2 and CH_4 Homogenous and heterogeneous reactions are fundamental in gasification process [17]. Energy balance was prepared in accordance with rule of Hess [18].

$$C + O_2 \rightarrow CO_2 \quad (2)$$

$$CO_2 = C + O_2 \quad (3)$$

$$\Delta H^o{}_{CO2} = -393.13 - 0 - 0 = -393.13\ kJ \quad (4)$$

$$2C + O_2 \rightarrow 2CO \quad (5)$$

$$2CO = 2C + O_2 \quad (6)$$

$$\Delta H^o{}_{CO} = -110.53 - 0 - 0 = -110.53\ kJ \quad (7)$$

$$C + 2H_2 \rightarrow CH_4 \quad (8)$$

$$CH_4 = C + 2H_2 \quad (9)$$

$$\Delta H^o{}_{CH4} = -74.78 - (0 - 2 \cdot 0) = -74.78\ kJ \quad (10)$$

$$C + CO_2 \rightarrow 2CO \quad (11)$$

$$2CO = C + CO_2 \quad (12)$$

$$\Delta H^o{}_{CO} = (2 \cdot -110.53) - 0 - (-393.13) = -221.06 + 393.13 = 172.07\ kJ \quad (13)$$

$$2CO + O_2 \rightarrow 2CO_2 \quad (14)$$

$$2CO_2 = 2CO + O_2 \quad (15)$$

$$\Delta H^o{}_{CO2} = (2 \cdot -393.13) - 2 \cdot 110.53 - 0 = -786{,}26 - 221{,}06 = -1007.32\ kJ \quad (16)$$

$$2CO + 2H_2 \rightarrow CH_4 + CO_2 \quad (17)$$

$$CH_4 + CO_2 = 2CO + 2H_2 \quad (18)$$

$$\Delta H^o{}_{CO2+CH4} = (-74.78 - 393.13) - 2 \cdot (-110{,}53) - (2 \cdot 0) = 246.85\ kJ \quad (19)$$

$$CO + 3H_2 \rightarrow CH_4 + H_2O \quad (20)$$

$$CH_4 + H_2O = CO + 3H_2 \quad (21)$$

$$\Delta H^o{}_{CH4+H2O} = (-74.78 - 241.60) - 2 \cdot (-110.53)(3 \cdot 0) = -537.44\ kJ \quad (22)$$

Enthalpy values of individual substrates were taken from thermodynamics tables [19]. If in the syngas there is no presence of higher hydrocarbons, this energy balance is adequate. Otherwise, if there are higher hydrocarbons higher than CH_4 syngas quality analyze is necessary for preparing chemical reactions

5 Evaluation of selected technological parameters

Evaluation of technological parameters like: syngas lower heating value, degree of carbon conversion to combustible substances and chemical efficiency were calculated in accordance with equation [20].

$$LHV_{syng} = \frac{126 \cdot uCO}{1000} + \frac{108 \cdot uH_2}{1000} + \frac{359 \cdot uCH_4}{1000}, \left[\frac{MJ}{m^3n}\right], \quad (23)$$

The syngas lover heating value during the stable work in function of time was shown in Fig. 3.

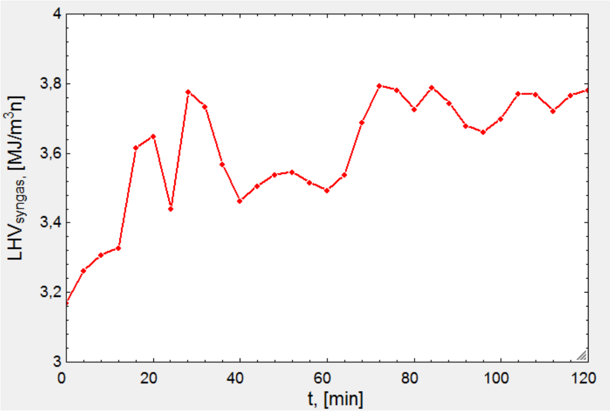

Fig. 3. Syngas lower heating value during steady state conditions in function of time

Average lower heating value of combustible syngas was 3,98 MJ/m^3. Lower heating value range was from 3,1 to 3,8 MJ/m^{3}n. During measurements the LHV value was fluctuated. The technological parameters used for process evaluation like chemical efficiency and carbon degree conversion were calculated in accordance with [2].
Syngas chemical efficency:

$$\eta_{\mathrm{chem}} = \left(\frac{\mathrm{St_{gas}} \cdot (\mathrm{yH_2} \cdot \mathrm{LHV_{H2}} + \mathrm{yCH_4} \cdot \mathrm{LHV_{CH4}} + \mathrm{yCO} \cdot \mathrm{LHV_{CO}})}{\mathrm{Stfuel} \cdot \mathrm{LHV_{fuel}}}\right) \cdot 100, [\%], \qquad (24)$$

Degree of carbon conversion in fuel:

$$C_{conw.} = \left(1 - \frac{St_{gas}(yCO_2\frac{12}{44} + yCO\frac{12}{28} + yCH_4\frac{12}{16})}{Stfuel \cdot yC}\right) \cdot 100, \ [\%], \qquad (25)$$

Where: St$_{gas}$ – Syngas content [m^3/h –efficiency, kmol/h – degree of conversion],y – gases content [-], LHV$_{H2,CO,CH4}$ – lower heating value of: hydrogen, carbon monoxide and methane [MJ/m^{3}n], St$_{fuel}$ – fuel stream [kg/h – efficiency, kmol/h –degree of conversion], LHV$_{fuel}$ –Lower heating value of fuel [MJ/kg], yC –mass content of carbon in combustible matter of fuel[-]

6 Balance of the process

Syngas molar stream was calculated in accordance with equation :

$$St_{fuel} + St_{air} = St_{syngas} + St_{ashes}, \left[\frac{kmol}{h}\right] \qquad (26)$$

Where: St$_{fuel}$–fuel stream [kmol/h] (St$_{fuel}$=0,08012), St$_{con}$– gasification agent stream [kmol/h] (St$_{con}$=0,08926), St$_{syngs}$ – syngas stream [kmol/h], St$_{ashes}$–ashes stream [kmol/h] (St$_{ashes}$=0,00296)

$$St_{syngas} = St_{fuel} + St_{air} - St_{ashes} = 0.139, \left[\frac{kmol}{h}\right] \qquad (27)$$

$$V_{syngas} = St_{syngas} \cdot 22.42 \left[\frac{m3}{kmol}\right] = 3.133, \left[\frac{m^3}{h}\right] \tag{28}$$

Stream volume of syngas was 3.133 m^3/h. While stream fuel delivered to the chamber was 1.256 kg/h (0,00802 kmol/h). The mass grade residue of combustible substance in ashes was 3%. Content of combustible substance from fuel stopped in ashes was calculated in accordance with equation :

$$X_{A1} = \frac{A \cdot X_A}{A1} = \frac{35.87 \cdot 3}{97} = 1.109, \qquad [\%], \tag{29}$$

Where: A – ashes content in fuel [%], X_A – combustible matter content in ash [%], A1 –incombustible matter content in ashes [%], X_{A1}- content of combustible substance from fuel stopped in ashes [%],

Mass stream of ashes was calculated in accordance with equation:

$$B_1 = B \cdot (A + x_{A1}) = 0{,}08012 \cdot 36.97\% = 0.464 \left[\frac{kg}{h}\right] \tag{30}$$

Where: B – fuel stream [kmol/h], A – ashes content in fuel [%], X_{A1}– combustible substance content in ashes [%]

7 Results

Results of syngas chemical efficiency and carbon conversion calculations were shown in Fig 4.

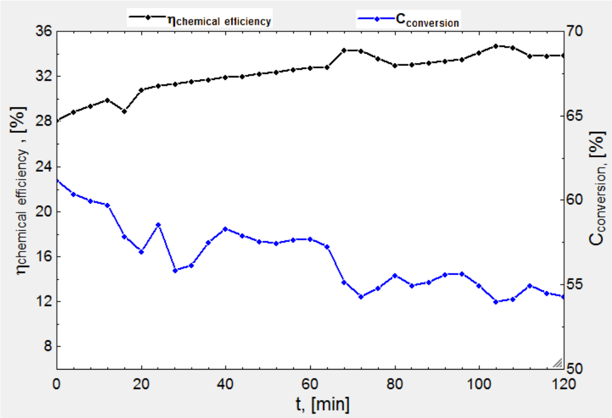

Fig. 4 Chemical efficiency of the process and degree of carbon conversion from sewage sludge in time.

Syngas chemical efficiency produced during municipal sewage sludge air gasification was in the range 33-35%. This value was slightly fluctuated in function of time. and mostly depends on lower heating value of fuel nd produced combustible gas. It also depends on humidity concentration in fuel. Increase of humidity cause decrease of calorific value what has been found by authors [21]. The degree of carbon conversion contained in combustible substance of fuel was in range 53-58%. Conversion changes depends on concentrations of gases in which composition one of the element was carbon. To this gases belongs CO, CH_4 and CO_2. In correlation with carbon element transformation gasification chemical efficiency is increasing while the decrease of carbon conversion. The highest efficiency (33%) was in achieved while the value of carbon conversion was 58%. And inversely 35% syngas efficiency was achieved in 54% carbon conversion. Transformation of coal element contained in combustible to carbon monoxide (incombustible gas) which not increase the lower heating value of syngas justify this dependence.

8 Conclusions

Evaluation of gasification process is possible with using selected technological parameters. Different values of parameters shown in this paper were depended on experimental conditions. Chemical efficiency was in correlation with degree of carbon conversion. Increase of chemical efficiency was increasing with syngas calorific value. One of the main gases that don't have influence on efficiency but on degree of carbon conversion was incombustible CO_2. Combustible syngas from fuel gasification is useful for power in forms of electricity and heat production. This product can be used in combined heat and power and integrated gasification combined cycle (IGCC) technologies. High efficiency gasification in this solution is one of the most desirable parameters. It means that evaluation of gasification processes is necessary to improve and find effective solutions for energy production.

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