Analysis of the possibility of landfill gas use as additional fuel for combustion of solid municipal waste with different moisture content

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Abstract. The paper suggested the calculation method of combustion for solid and gaseous fuel cofiring. The calculation is suggested to carry out for per unit of generated during combustion total capacity instead of per unit of weight or volume of fuel. This method was tested during combustion parameters examination at cofiring of solid municipal waste, which is the main fuel, and landfill gas (biogas) which is the additional fuel for thermal mode stabilization. The calculation has been conducted for waste with the moisture content of 50%, 30% and 10%, which are solid fuel, methane, as a reference fuel, common biogas with a methane content of 60%, and biogas with a low methane content of 35%. It was established that additional input of biogas is effective for the combustion of unprepared waste with high moisture content, moreover, it is possible to use common biogas as well as biogas with low methane content. The required combustion product temperature (900-1000°C) for unprepared waste can be achieved at the excess air coefficient of 11 6 or more. In summary, solid fuel and biogas cofiring allows operative control of the combustion process and sustain combustion product temperature and heat output of units at a constant level. The combustion process regulation should be based on the given temperature of combustion products by changing two parameters: landfill gas flow rate and flow rate of air supplied for combustion.

1. Introduction

Currently, there is no technology for solid municipal waste utilization that combines economic efficiency and environmental safety. Because of this, most of the waste management systems in Europe employ low-cost ways of utilization [1]. Combustion, which is the most common way of utilization, is difficult to use in medium or small size communities due to inadequate output production of plants [2].

The paper [3] has analyzed four variants of combustion of leftovers which are formed after a useful fraction, that goes for recycling, is removed from the municipal waste. The research studied combustion of waste on the grate without preparation, mechanically pre-grinded, prepared from the RDF leftovers, and firing in the fluidized bed combustion chamber. It has been established that the mechanical pre-processing and increase of the heat value have a minor effect on the energy efficiency of the thermal waste recycling plant, but significantly increase the cost of the technology and energy consumption. The most energy-saving is achieved when waste is incinerated without pre-processing at the large-scale plants.
The paper also states another conclusion that the pre-processing of waste before combustion doesn’t have any energy and ecological advantages. This is because expenses for grinding and drying cannot be covered by the energy production from waste and by an improvement of the environmental indexes [4]. Besides, the preparation of waste for RDF production requires its grinding and drying which creates a large number of toxic gases [5]. The paper [6] points out that because of the much lower mean heating value the untreated solid municipal waste combustion creates a high risk of toxic matter emission due to incomplete combustion and much lower potential recuperation of energy. The paper [5] presents data that the food waste content doesn’t impact the hazardous emission composition, but it worsens when wood construction parts are incinerated (windows, doors, beams, and so on, that resulted after building demolitions).

The exhaust gas cleaning from hazardous particles removes them only from the gas but harmful particles still stay in the cleaning waste [7]. During the waste combustion, the decrease of the amount of emissions depends on the control of processes in the combustion chamber but not on the waste composition [8]. In summary, the most efficient way of harmful emission amount reduction is a combustion mode control during waste incineration to ensure the required temperature level and complete burning [6, 9]. By the temperature and excess air values adjustment, using CO content in the exhaust gas as the controlled parameter, it is possible to determine and sustain the optimal combustion conditions that result in dioxin and furan emissions minimization [10].

To sustain combustion without using a secondary fuel, the incoming waste should have a moisture content not more than 50%, operational ash content lower than 60%, and combustible material content in the as-fired mass of more than 25%. The excess air coefficient should be at 1.6-1.8 [11].

During biomass combustion for combustion temperature increase and mode stabilization, when biomass quality fluctuates, the cofiring with natural gas is used [12, 13]. The efficiency of the plant operation during several fuel types cofiring heavily relies on the fuel combustion mode and conditions, and the necessary thermal modes should be provided within the entire range of burnt fuel mixes [14]. During several fuels cofiring the hazardous emission content, heating surface fouling tendency, and bed sintering nonlinearly depend on variations of fuel mixtures. Often, the only way to obtain information on fuel mixtures cofiring specifics are studies in the experimental or commercial plant [14].

The primary target of waste and gaseous fuel cofiring is a stabilization of heat release in the furnace and boiler ignition process simplification and reduction of the increased emissions which are common for this process [7]. Also, an increase of the gas flow temperature leads to complete incineration of the inside flow solid fuel particles and organic compounds which are formed during a low temperature or incomplete combustion [15]. The load stabilization requires an input of natural gas in the amount of up to 20% from the plant’s heat output to decrease emission content by 10-15% [7]. The cofiring significantly decreases emissions that are formed during waste combustion [16].

The municipal solid waste landfills are the source of the landfill gas – biogas that contains components such as methane CH4 (35-60%), carbon dioxide CO2 (20-40%), and nitrogen N2 (up to 40%). The landfill gas also requires utilization [17] because, according to the various estimates, the methane greenhouse effect exceeds the carbon dioxide greenhouse effect by 25-70 times [18]. The low biogas heating value, a large amount of CO2, and impurities are the main obstacles that prevent its use in power generating plants [19, 20]. As far back as 1990, the Gas Research Institute (USA) has developed the combustion system for SMW furnaces that utilizes a small amount of natural gas and landfill gas cofiring [7]. This has allowed to control the dioxin and furan emissions and simultaneously stabilize the plant’s heat output. The research was conducted on two steam boilers that were burning waste with a consumption rate of 13,600 t/h and 90,7 t/h. Initially, the boilers were designed for RDF and coal cofiring but the operation has demonstrated the inefficiency of this approach due to abrupt and uncontrolled load fluctuations because of the RDF content variations up to 20-25%, ignition difficulties, and a large amount of hazardous emissions. The two-level burner was developed for RDF, landfill, and natural gas cofiring. The burners for natural gas were placed at the furnace’s lower part above the grate and provided 10% of the heat load. The burners for landfill or natural gas combustion were placed in the middle of the furnace which also provided 10% of the load (Fig. 1).
Presently, the commercial furnaces designing is carried out, most of the time, using approximate empirical equations [21]. The paper [22] has conducted an analysis of the SMW combustion temperature at the low power water heating boiler with a grate in relation to SMW moisture content, excess air coefficient, the temperature of the supplied for combustion air and amount of the extracted heat and also the parameter range was determined that helps to maintain the required combustion temperature of 900…1100°C, which leads to a complete distraction of inside waste organic hazardous substances but prevents ash melting and formation of sintered mass. It was concluded that the necessary temperatures can be maintained within a wide range of the mode parameters and SMW moisture content. The paper [23] has analyzed biogas combustion and the conclusion was made that in order to maintain the combustion parameters it is necessary to use swirl burners.

The paper’s objective is the combustion calculation method development for waste (solid fuel) and biogas (gaseous fuel) cofiring, the examination of the combustion parameters for different levels of waste preparation (moisture content), methane content in biogas, and the amount of gaseous fuel supplied for burning.

Therefore, to determine the possibility of unprepared or prepared waste and biogas cofiring it is necessary to establish the possibility of obtaining the necessary temperatures.

2. Materials and Methods

2.1. Units of specific calculation and flow rate of fuels
It is suggested to carry out the calculation for per unit of generated during combustion total capacity. In this case, the mass specific flow rate of the solid fuel:

\[ m_s = (1 - q_g)/Q_s, \text{ kg/MW}; \] (1)

a volumetric specific flow rate of landfill gas:

\[ v_g = q_g/Q_g, \text{ m}^3/\text{MW}, \] (2)

where:
\( q_g \) – part of the energy released during landfill gas combustion in overall energy;
\( Q_s \) – a lower heating value of solid fuel, MW/kg;
\( Q_g \) – a lower heating value of landfill gas, MW/m^3.
If the solid fuel mass flow is given then the landfill gas volumetric flow rate can be calculated using the equation

\[ v_g = (1 - m_s Q_s)/Q_g, \] (3)

in the opposite case

\[ m_s = (1 - v_g Q_g)/Q_s. \] (4)

### 2.2. Calculation of moisture content in biogas

Biogas has a high moisture content. This is due to the fact that it forms in an environment where the temperature is 40-60°C and moisture content is 40-50%. When biogas is cooled to the outside temperature the excessive moisture condenses and the water vapors in gas, normally, are in the saturated state when the relative humidity of biogas is \( \phi = 100\% \).

Gas moisture content \( d, \text{kg/kg} \), is defined by the relation of a water vapor mass to a mass of dry part of gas. For 1 kg of dry gas and \( d \) kg of vapors the equations of state can be presented as follows:

\[ p_w V = d R_w T; \] (5)

\[ p_{dg} V = R_{dg} T; \] (6)

where:

- \( V \) – volume;
- \( T \) – temperature;
- \( p_w \) and \( p_{dg} \) – water vapor and dry gas pressure, Pa, the sum of their values equal to the barometric pressure \( p_b \), Pa;
- \( R_w \) and \( R_{dg} \) – gas constants for water vapors (\( R_w = 461.520 \text{ kJ/(kg·K)} \)) and dry gas, the gas constant of a gas mixture is defined on the volume fraction of components \( v_i \) and their gas constants \( R_i \): \n
\[ R_{dg} = \frac{1}{\sum v_i R_i} \] (7)

When we divide the equation (5) by (6) we obtain the expression for gas moisture content determination with respect to the gas relative humidity \( \phi = p_w/p_b \cdot 100\% \):

\[ d = \frac{p_{dg}}{p_b - p_{dg}} \frac{R_{dg}}{R_w} = \frac{\phi p_s}{100 p_b - \phi p_s} \cdot \frac{R_{dg}}{461.520} \] (8)

For the water vapor saturation pressure calculation \( p_s \), Pa, in relation to temperature \( t, \degree C \), the regression equation was obtained which is applicable within the temperature range \(-30…100\degree C\), the mean square deviation is 138:

\[ p_s = \exp((6.4 + 0.10128 \cdot t)/(1 + 0.00434 \cdot t)) \] (9)

For the air with \( R = 287.520 \text{ kJ/(kg·K)} \) the equation (8) can be written as follows:

\[ d_{air} = 0.622 \frac{\phi p_s}{100 p_b - \phi p_s}. \] (10)
2.3. Calculation of solid and gaseous fuel cofiring
The waste chemical composition is presented by the following elements:

\[ C^c, H^r, O^r, N^r, S^r, A^r, W^r, \text{mass } \% \]

Gaseous fuel content:

- \( \text{CH}_4, \text{C}_2\text{H}_6, \text{C}_3\text{H}_8, \text{C}_4\text{H}_{10}, \text{C}_5\text{H}_{12}, \text{CO}_2, \text{H}_2, \text{H}_2\text{S}, \text{O}_2, \text{N}_2, \text{volume } \% \)

The theoretical volume of air necessary for combustion, \( m^3/W \):

\[
V_{\text{air}}^0 = \frac{1}{29.87} \cdot (2.67C^c + S^r + 8H^r - O^r) \cdot m_s + \\
+ 0.0476 \cdot (0.5H_2 + 2CH_4 + 3.5C_2H_6 + 5C_3H_8 + 6.5C_4H_{10} + 8C_5H_{12} + \\
+ 1.5H_2S - O_2) \cdot v_g
\]

(11)

Actual volume of moist air necessary for combustion, \( m^3/\text{MW} \):

\[
V_{\text{air}} = \alpha V_{\text{air}}^0 \cdot (1 + 1.293 / 0.805 \cdot d_{\text{air}})
\]

(12)

Combustion product composition, \( m^3/\text{MW} \):

\[
V_{\text{cp CO}_2} = 0.01 (1.87C^c + 0.7S^r) \cdot m_s + \\
+ 0.01(\text{CO}_2 + \text{CH}_4 + 2\text{C}_2\text{H}_6 + 3\text{C}_3\text{H}_8 + 4\text{C}_4\text{H}_{10} + 5\text{C}_5\text{H}_{12} + \text{H}_2\text{S}) \cdot v_g
\]

(13)

\[
V_{\text{cp H}_2\text{O}} = (0.111\text{H}^r + 0.012\text{W}^r) \cdot m_s + \\
+ 0.01(\text{H}_2 + 2\text{CH}_4 + 3\text{C}_2\text{H}_6 + 4\text{C}_3\text{H}_8 + 5\text{C}_4\text{H}_{10} + 6\text{C}_5\text{H}_{12} + \text{H}_2\text{S}) \cdot v_g + \\
+ \alpha V_{\text{air}}^0 \cdot 1.293 / 0.805 \cdot d_{\text{air}} + \rho_{g} / 0.805 \cdot d_{g} \cdot v_g
\]

(14)

\[
V_{\text{cp N}_2} = 0.79\alpha V_{\text{air}}^0 + 0.008\text{N}^r \cdot m_s + 0.01\text{N}_2 \cdot v_g
\]

(15)

\[
V_{\text{cp O}_2} = 0.21(\alpha - 1) V_{\text{air}}^0
\]

(16)

where:

- \( d_{\text{air}} \) – moisture content of air, kg of moisture/kg of dry air;
- \( d_{g} \) – moisture content of gaseous fuel, kg of moisture/kg of gas;
- \( \rho_{g} \) – gaseous fuel density, kg/m\(^3\);
- \( \alpha \) – excess air coefficient.

The presented expressions (11) - (16) can be also applied in per unit of fuel calculation. In the calculation of the specific values for 1 kg of solid fuel the flow rates are as follows:

\[
m_s = 1 \text{ kg}; \quad v_g = \frac{q_g \cdot \rho_g}{1 - q_g \cdot \rho_g} \cdot \frac{m^3 \text{ of gas}}{\text{kg of solid fuel}}
\]

(17)
and in calculation for 1 m\(^3\) of biogas:

\[ v_g = 1 \ m^3; \quad m_s = \frac{1 - q_g Q_g}{q_g Q_s}, \quad \text{kg of solid fuel} \quad m^3 \text{of gas}, \]  

(18)

3. Results and Discussion

For the research, several average composition types of solid municipal waste with different moisture content were used: unprepared with the moisture content of 50%, partially dried waste with the moisture content of 30% and 10%, which are typical for RDF (Table 1). To recalculate composition with reference to the required moisture content the method presented in the paper [24] was used.

| Item                     | Chemical composition, mass % | Heating value \(Q_{in}, \text{kJ/kg}\) |
|--------------------------|-----------------------------|----------------------------------------|
| RDF                      | C 34.4, H 4.6, O 23.0, N 0.9, S 0.3, A 26.9, W 10.0 | 13 655                                 |
| Partially dried MSW      | C 26.8, H 3.6, O 17.9, N 0.7, S 0.2, A 20.9, W 30.0 | 10 063                                 |
| Unprepared waste         | C 19.1, H 2.5, O 12.8, N 0.5, S 0.1, A 15.0, W 50.0 | 6 470                                  |

In the paper [25], based on the examination of biogas release at the MSW landfills, it was established that the composition of landfill gas is very uneven. Therefore, three variants of additional gaseous fuel were considered: methane as the reference fuel, common biogas with a methane content of 60%, and biogas with a low methane content of 35% (Table 2). The biogas composition was given on the basis of mean values obtained using the instrumental measurements. Only three components were considered due to the insignificant presence of the rest in gas.

| Item                                      | composition, volumetric % | Density \(\rho, \text{kg/m}^3\) | Heating value \(Q_{in}, \text{kJ/m}^3\) |
|-------------------------------------------|---------------------------|---------------------------------|----------------------------------------|
| Methane                                   | CH\(_4\) 100, CO\(_2\) 0, N\(_2\) 0 | 0.716                           | 35 820                                 |
| Common biogas                             | CH\(_4\) 60, CO\(_2\) 20, N\(_2\) 20 | 1.072                           | 21 492                                 |
| Biogas with low methane content           | CH\(_4\) 35.0, CO\(_2\) 43, N\(_2\) 22 | 1.370                           | 12 537                                 |

Biogas contains a large amount of moisture [26]. When biogas is cooled down from the temperature of the landfill body (40-60°C) to the atmosphere temperature, which takes place during pipeline transportation to the point of use, the excessive moisture turns into condensate and the relative humidity at the point of use becomes 100%. Figure 2 presents biogas moisture content influence on the theoretical combustion temperature which takes into account a dissociation of triatomic gases. The highest influence can be seen for biogas with low methane content due to its high density.
When waste is dried in the rotary drier 6x20 m with a 1 t/h output capacity of waste with a moisture content of 50% the natural gas flow rate for drying agent heating is 50 m$^3$/h. Therefore, the heating value of the obtained fuel is 1.8 MW (6.5 GJ/h), and the heat energy of the gas used for drying is 0.5 MW (1.8 GJ/h). In view of this, waste recycling into RDF involves high energy consumption. However, the necessary combustion temperature (900-1000°C) can be achieved during the combustion of waste even with a moisture content of 50%.

The study (Figure 4) has demonstrated that additional combustion of natural gas always increases combustion temperature. Common biogas increases combustion temperature for the unprepared waste with high moisture content, for the dried waste its combustion leads to a slight temperature decrease. Biogas with low methane content can increase the combustion temperature only for unprepared waste.
Since waste and biogas combustion at the excess air coefficient close to the lower limit can provoke underburning the study was carried out to determine at what values of $\alpha$ the combustion product temperature is 1000°C (Figure 5).

![Figure 5](image)

**Figure 5.** The excess air coefficient $\alpha$ that allows reaching the combustion temperature of 1000°C when waste moisture content varies.

According to the obtained dependences even for the moist waste, the required combustion temperature can be provided at an excess air coefficient of 1.6 without the additional combustion of gas.

4. **Conclusion**

The solid fuel and biogas cofiring allow the operative combustion process control and sustain combustion product temperature and heat output of units at a constant level. The additional input of biogas is useful for the combustion of unprepared waste with high moisture content, besides, it is possible to use common biogas as well as biogas with low methane content. The combustion process control should be based on the given combustion product temperature value by changing two parameters: landfill gas flow rate and flow rate of air supplied for combustion.

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