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Influence of the Waste Biomass Gasification Gas Composition on the Laminar Flame Speed Values

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As a result of the gasification of the organic matter of biomass achieved a gas, which can be used in many ways. It can be burned in the engine, gas turbine or boiler, it can also be a substrate for the chemical processes. However, gas from gasification may, be characterised by high variability in composition depending on the process conditions and fuel composition before process. For this reason, its use may pose some difficulties. For example, it may be the design of burners and combustion chambers to ensure environmentally and energy efficient disposal. For this reason it is extremely important to know the basic properties of the gas. Laminar flame speed is a key parameter to be taken into account during designing equipment for the gas utilisation.
The paper presents the results of experimental investigation of the laminar flame speed of the different kind of biomass gasification gases. Bunsen burner method was used. Additionally, the temperature distribution in the flame was determined. The results show that there are optimum conditions for conducting combustion of the biomass gasification gases, with which it is possible to carry out the stable process with effective heat release. The results indicate that low calorific gases from the thermal processing of biomass can be a source of fuel for the production of the final forms of energy.

1. Introduction

Biomass is one of the major sources of energy that is estimated to contribute between 10 % and 14 % of the world's energy supply. Over the past several years, several countries have established policy targets to increase their production of renewable energy from biomass. The thermo-chemical conversion of biomass can be done by four main processes: combustion, co-combustion, gasification and pyrolysis. The most promising and perspective technology is gasification. Gasification has several advantages over a traditional combustion process. As a consequence of the reducing atmosphere, gasification prevents emissions of sulphur and nitrogen oxides, heavy metals and the potential production of chlorinated dibenzodioxins and dibenzofurans. A smaller volume of gas is produced compared to the volume of flue gas from combustion because gasification is characterised by an environment containing low levels of the gasification agent.
The gasification process of biomass attracts increasing research interest in the field of energy. Synthesis gas (syngas) derived from the biomass gasification process with primary content of hydrogen, carbon monoxide, methane and some inert component like nitrogen, carbon dioxide and water vapour, is considered to be important for further energy conversion and utilisation (Wang et al., 2015). However, variations of biomass feedstock and gasification process operating parameters significant change in the component of syngas (Bibrzycki et al., 2014). Typically its composition varies from 4.0 % to 50.4 % hydrogen, 8.1 % - 60.5 % carbon monoxide, 1.3 % - 29.6 % carbon dioxide, 0 % - 20.4 % water vapour and 0 % - 9.3 % methane (Frassoldati et al., 2007). This feature introduces a big challenge for the design burners and combustion chambers, especially aiming at low emission. Therefore, it is crucial to understand the fundamental combustion properties of syngas with components diversity. Among flame properties, the laminar flame speed is regarded as an important parameter because it serves as a basis to turbulent combustion, and it also contains the fundamental information on the reactivity. Additionally, the laminar flame speed controls other key combustion characteristics, such as the flame's spatial distribution.

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Additionally, the laminar flame speed is also one of the fundamental parameters that helps validate chemical kinetics models and aids the design of the combustor (Lee et al., 2014). Different methods have already been reported applied to the measurement of the laminar flame speed of syngas, such as flat flame, Bunsen flame, stagnation flame, spherically propagating flame, counter-flow flame and heat flux method (Bouvet et al., 2011).
Due to its flexibility and simplified operating conditions, the Bunsen flame approach has been chosen to investigate the laminar flame speed of gasification gas gasification process of two different types of sewage sludge for a wide range of air ratio at atmospheric pressure and ambient temperature. A particular emphasis has been put on the syngas flame stability domain.

2. Experimental approaches

2.1 Materials and methods

Syngas from the gasification process of two types of sewage sludge SS1 and SS2 feedstock were analysed. SS1 was taken from Polish wastewater treatment plant operating in the mechanical-biological system and SS2 was taken from mechanical-biological-chemical wastewater treatment plant with phosphorus precipitation. In both analysed cases, the biological part of the wastewater treatment plant has worked with low load activated sludge. Thanks to it, effective removal of nutrients (phosphorus and nitrogen) from wastewaters is allowed. Additionally, in both analysed cases, sewage sludge is stabilised by anaerobic digestion and dehydration. So, after anaerobic digestion, sewage sludge is dried. In Table 1 main properties of sewage sludge gasified are presented. The sewage sludge gasification tests were conducted using a fixed bed gasification facility. It was described earlier (Werle, 2011). In Table 2 compositions of the syngas taken to analysis are presented.

Table 1: Main properties of the sewage sludge (Werle, 2012)

	Symbol of sewage sludge	
	SS1	SS2
Waste treatment plant configuration	mechanical-biological	mechanical-biological-chemical
Proximate analysis, % (as received)		
Moisture	5.30	5.30
Volatile matter	51.00	49.00
Ash	36.50	44.20
Ultimate analysis, % (dry basis - d.b.)	31.79	27.72
C	4.36	3.81
H	4.88	3.59
N	57.07	63.04
O (by difference)	1.67	1.81
S	0.013	0.003
F	0.22	0.03
Cl		
Calorific value, MJ kg^{-1} (on dry basis) HHV	14.05	11.71

Table 2: Composition of the analysed syngas

Symbol	Feedstock gasified	Syngas composition, % vol.					
		CO	CO_2	H_2	CH_4	N_2	LHV, MJ/m^3_n
Syngas1	SS1	28.5	15.0	5.0	1.0	50.5	4.49
Syngas2	SS2	25.0	18.0	3.5	0.8	52.7	3.81

The Bunsen flame method is based on the determination of the geometric shape of the inner combustion (kinetic) cone and calculating the angle α, which allows to compute the laminar flame speed. This angle can be determined, as the angle between the slant height of inner cone and the base of this cone. In this method it is assumed that the inner cone has an ideal cone shape, and the mixture flow speed is constant throughout the cross-section of the burner. The experiment was carried out for two different gas streams - 500 and 600 L/h for both syngas compositions. Experimental installation is presented in Figure 1.

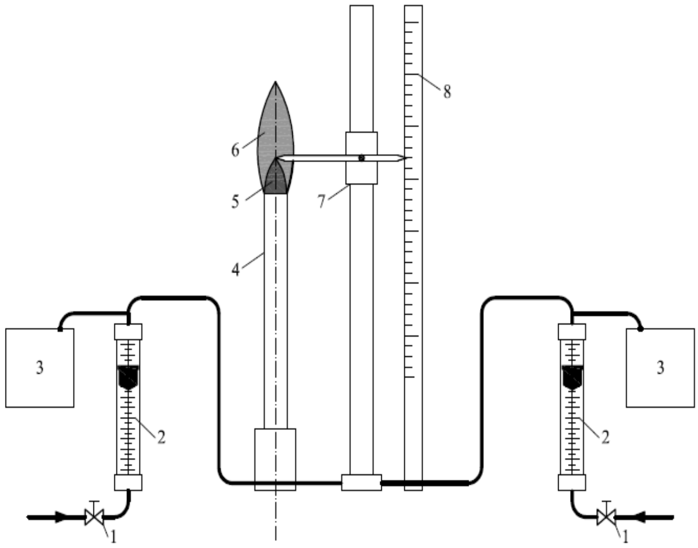

Figure 1: Laboratory stand used during the experiment (1-valves, 2-rotameters, 3-manometers, 4-burner, 5-inner combustion (kinetic) cone, 6 - outer (diffusive) combustion cone, 7-stand with a movable pointer, 8-ruler)

2.2 The calculation algorithm

Effective flame speed was calculated using Eq(1)

$$S_e = \frac{\dot{V}_{gr} + \dot{V}_{ar}}{\pi \cdot \frac{D^2}{4}} \tag{1}$$

where: S_e – effective flame speed, m/s; $\dot{V}_{gr}$ – real gas flow, m^3/s; $\dot{V}_{ar}$ – real air flow, m^3/s; D – diameter of burner, m;

The air ratio (λ) was calculated according Eq(2) taking into account the combustion air and fuel ratio $\frac{m_{air}}{m_{fuel}}$, the minimum amount of air $\frac{1}{n_{airmin}}$ required for complete combustion and the molecular weight of air $\frac{1}{M_{air}}$:

$$\lambda = \frac{m_{air}}{m_{fuel} \cdot n_{airmin} \cdot M_{air}} \tag{2}$$

The angle α was determined. The angle α is the angle between the laminar flame speed vector and the effective flame speed vector. Using the similarity of the triangles it can be concluded that it has the same value as the angle between the radius R of the burner and the slant height of the inner combustion cone:

$$\alpha = arctg\left(\frac{H}{R}\right) \tag{3}$$

where: α - angle between the laminar flame speed vector and the effective flame speed vector, ^{0}; H – height of the inner combustion cone (which was measured during the experiment), m; R – radius of the burner (which was measured during the experiment), m.

Laminar flame speed was calculated using the following formula:

$$S_L = S_e \cdot \cos \alpha \tag{4}$$

where: S_L – laminar flame speed, m/s.

3. Results and discussion

Figure 2 shows laminar flame speed values as a function of air ratio for two different gas streams - 500 and 600 L/h and for both analysed syngas.

a)

b)

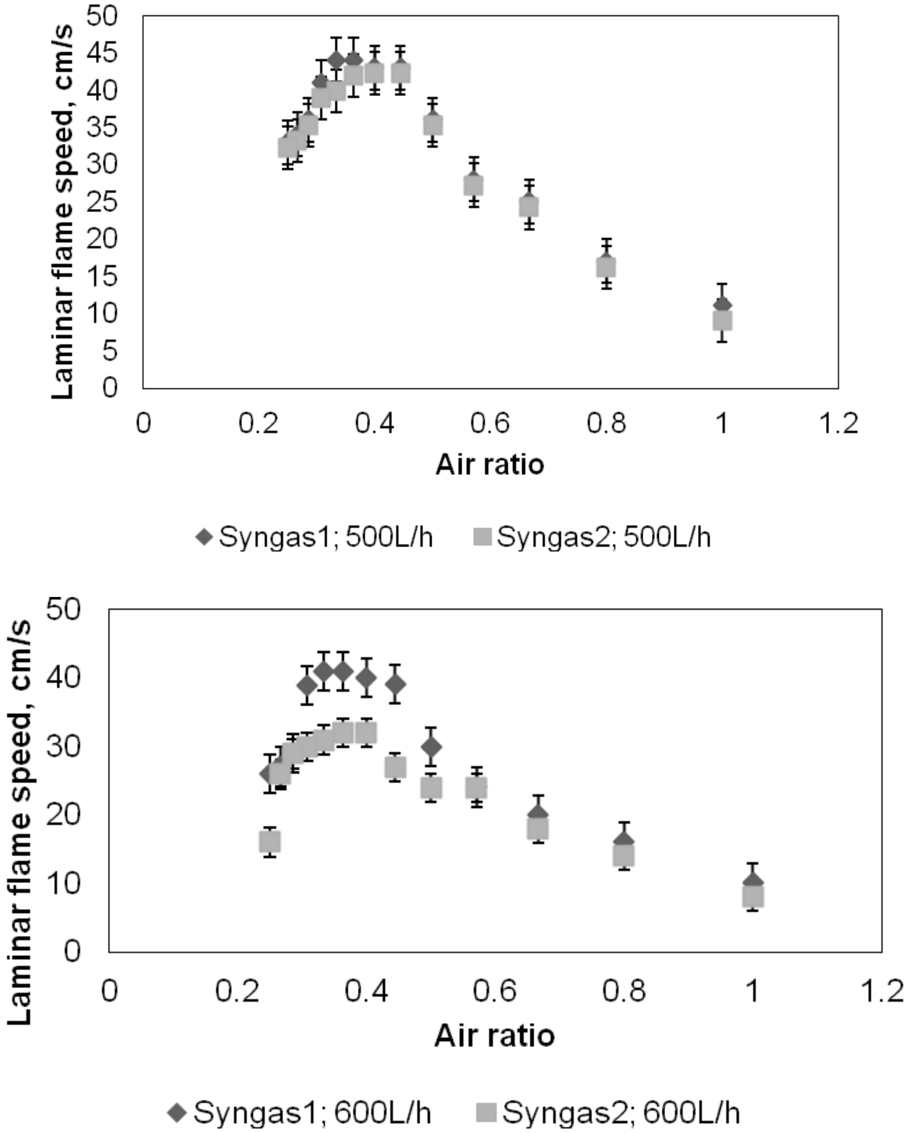

Figure 2: Laminar flame speed as a function of air ratio

The laminar flame speed of analysed syngases reaches its maximum at fuel rich condition. It can be also observed, that the laminar flame speed value increases as the molar fraction of hydrogen in the fuel goes up. In the case of the Syngas1 (molar fraction of hydrogen equal to 5 %) the laminar flame speed is equal to 44.1 cm/s (for volumetric gas streams equal to 500 L/h) and 41.0 (for volumetric gas streams equal to 600 L/h) and in the case of Syngas2 (molar fraction of hydrogen equal to 3.5 %) – 42.3 cm/s (for volumetric gas streams equal to 500 L/h) and 32.0 (for volumetric gas streams equal to 600 L/h). This behaviour is explained by the facts that the overall reactivity of the fuel mixture increases with the amount of hydrogen and the low molecular weight of hydrogen acts to increase the diffusivity of the reactant mixture. This is mainly due to the well-known sensitivity of the carbon monoxide oxidation rate to the presence of small amounts of hydrogen containing species. The main carbon monoxide oxidation shifts from slower reaction (R1) to relatively faster (R2) as the amount of hydrogen increases, causing an increase in laminar flame speed.

$CO+O \rightarrow CO_2$ (R1)

$CO+OH \rightarrow CO_2+H$ (R2)

It should be also mentioned that hydrogen pose a very unique combustion characteristics which differs significantly from hydrocarbon fuels. Above the value of the air ratio in which laminar flame speed reaches its maximum, there is visible slightly decrement of this parameter. It can be explained by the presence of unwanted carbonyl compounds in the hydrogen/carbon monoxide blend. These compounds tended to have strong inhibition effects on flames and were essentially effective on the rich side of the laminar flame speed curve.

Laminar flame speed results achieved using the Bunsen flame method was compared with kinetic model results. The GRI-Mech 3.0, originally developed for methane combustion, consists of 53 species and 325 reactions were used. This mechanism includes reactions that are involved in the combustion of other hydrocarbon fuels, such as ethane and propane. In recent years, this mechanism has also been employed for CH_4/H_2/air and H_2/CO/air flame simulations. The comparison of Syngas1 (500 L/h) results with kinetic predictions is presented on Figure 3. Analysing results presented in this figure it can be concluded that experiment curve has a shape similar to the shape of a bell curve, which has a maximum at $\lambda \leq 1$. The results obtained from measurements are only a fragment of the bell curve. Determination of the laminar flame speed for higher air ratio values was not possible because the flame was blown off. Although the laminar flame speed obtained based the Bunsen flame method wasn't adiabatic, the results showed to be very close to the kinetic prediction using GRi-Mech 3.0 mechanisms. Hence, the Bunsen flame method showed to be reliable in certain air ratio zone and can be used to validate the simulation results.

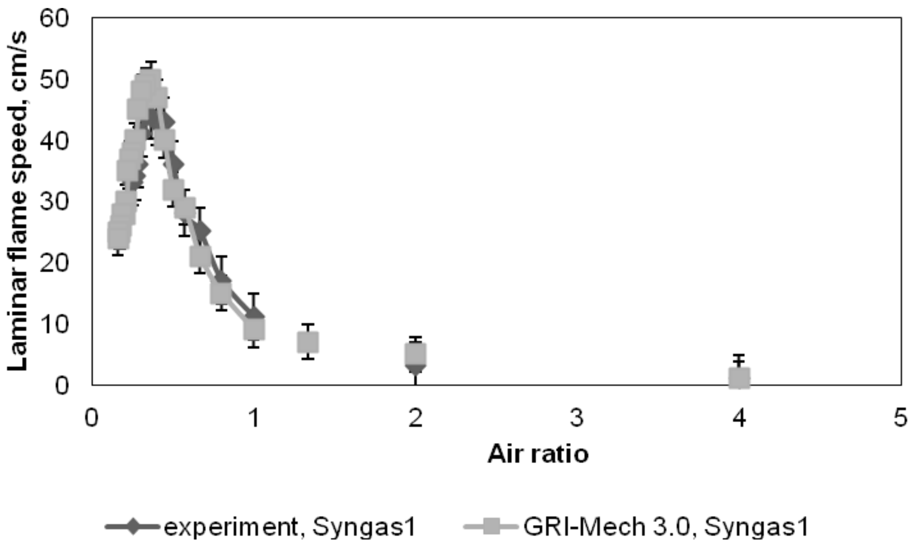

Figure 3: Laminar flame speed results – comparison of the experiment and kinetic results

4. Conclusions

For the power and heat sector, gasified biomass can be used as a fuel in combustion devices such as gas engines, gas turbines, boilers or industrial burners. Particularly, use of the gasified biomass for energy final energy generation is foreseen as a very promising application, possessing great potential for research and development. The combustion of gasified biomass differs from that of natural gas particularly due to its different composition of heating value. Therefore, it is crucial to understand the fundamental combustion properties of syngas with components diversity. Results show that the laminar flame speed value increases as the molar fraction of hydrogen in the fuel goes up. This is mainly due to the well-known sensitivity of the carbon monoxide oxidation rate to the presence of small amounts of hydrogen containing species. The high diffusivity of hydrogen atom and molecule influences the combustion characteristics of syngas. Analysing compared results achieved using Bunsen flame method experiment and kinetic prediction using GRI-Mech 3.0 mechanisms it can be concluded that this simple, cheap and flexible method can be used to validate the simulation results.

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