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A microwave plasma potential in producer gas cleaning — preliminary results with a gas derived from a sewage sludge

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Abstract

The presented work was to estimate an efficiency of a microwave plasma as a potential method of a sewage sludge derived producer gas cleaning. Obtained results showed a high effectiveness of the microwave plasma in conditioning of the producer gas. Its application resulted in a significant rise of CO and H₂ in the gas. What's more, the increase in CO concentration was not only a result of hydrocarbons conversion, but also CO₂ reduction. The decomposition efficiency of hydrocarbons depended on the species type. In case of C1-C2 the conversion was about 60–70%. Slightly higher decomposition was achieved for benzene. The decomposition rate of compounds heavier than C2 and lighter than benzene exceeded 90%. A similar conversion was achieved in case of species heavier than benzene. This includes toluene, which concentration, depending on the run, decreased from about 4 g/Nm³ to levels even lower than 10 mg/Nm³. These results seem crucial from the tar conversion point of view.

Keywords: Sewage sludge; Gasification; Tar; Microwave plasma

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1 Introduction

Sewage sludge, due to its properties, might be considered as an alternative fuel [1]. Recently, a great interest has been given to the sewage sludge as an energy source. This interest is derived from two main reasons. Firstly, climate change gave a priority to ecological policy in many countries. Hence, a great pressure is put on decreasing a conventional energy production connected with fossil fuels and replacing it with a one that is environmentally sound. This attitude is dictated not only by an increasing CO₂ emission – it is also connected with a decline of fossil fuels resources. Biomass, including sewage sludge, seems to fit perfectly into a green policy. It is considered neutral in terms of carbon dioxide emission and can be used instead of conventional fuels. Secondly, sewage sludge, which originates from wastewater treatment, is becoming a significant problem to developed countries. The amount of sewage sludge produced in Europe is continuously increasing [2]. Moreover, it seems that in the nearest future landfilling – the easiest way of sewage sludge disposal – is going to be drastically restricted [2]. Thus, thermochemical conversion technologies may be essential in terms of sewage sludge utilization.

Implementing thermochemical processes in a sewage sludge treatment shows many advantages, e.g., reducing of sewage sludge volume and destruction of pathogens. Moreover, it gives a possibility to recover energy. It is most promising in case of gasification, since its products might be used for generation of heat and electric energy, but also in production of valuable chemical compounds.

There are many examples of successful gasification of sewage sludge in both the laboratory [3–5] and the commercial scale [6,7]. Nevertheless, gasification of biomass is unavoidably connected with tar generation. Tar can be defined as a mixture of aromatic compounds characterized by a molecular mass higher than that of benzene [8]. Despite this definition, benzene is often considered when the tar composition is analyzed [9]. Due to its condensable nature, presence of tar can result in blocking of pipelines and fouling of engines and turbines [10]. Thus, tar is a major factor that limits the producer gas potential – its removal is crucial for a widespread commercialization of biomass gasification technology.

Methods used for a tar removal can be divided into two groups: primary and secondary methods. The first one is based on controlling of the gasification process, that means modification of a gasifying reactor, fuel's properties and optimization of the process conditions [11–13]. These methods are fundamental and enable a general process improvement – including decreasing of tar concentration – without significant investment costs and external devices. However, a really efficient removal of tar requires application of external devices. Secondary methods in-

clude thermal, mechanical, catalytic and plasma methods. These methods and their comparison were well described in many review works [10,13–16]. This work is focused on plasma methods, which, next to catalytic one, show the highest efficiency in tar removal [17,18]. The advantage of this method, in comparison to mechanical one, is that it does not only separate tar from the gas, but it also converts it into valuable products, like H_2 , CO or light hydrocarbons [19]. Moreover, it was shown that plasma provides conditions which allow reducing CO_2 into CO – a demand product in gasification process [20–22]. Additionally, plasma methods can be easily matched with other, e.g. catalytic one [23,24], providing heat necessary for the latter and showing a higher efficiency than any of those methods on its own [25].

Plasma shows a great potential in tar decomposition due to its properties. It is not only a source of high temperature but also a medium that consist of ions and radicals which can enhance chemical processes [26,27]. Although plasma can be created using of many energy sources in very different reactors [26,27], two types of plasma reactors were mainly used in research focusing on tar decomposition, pulsed corona plasma [18,28,29] and gliding arc plasma [21,30,31], though the latter one seems to supersede the first one. However, recent years brought a greater interest in catalytic methods rather than plasma. On the other hand, microwave plasma was barely investigated considering tar removal [32]. Nevertheless, it was proved that implementing microwave plasma can be an effective way of hydrogen production and methane conversion [33].

This paper presents the preliminary results of applying microwave plasma in decomposition of aromatic compounds in the gas derived from the sewage sludge gasification.

2 Sewage sludge for experiment

The sewage sludge used in this study was sampled from a wastewater treatment facility in Polish city Żary. The material was dried in a greenhouse after anaerobic digestion treatment. The results from proximate (analytical state) and ultimate analyses of the sewage sludge are given in Tab. 1.

Table 1: Proximate and ultimate analyses of the sewage sludge.

Proximate analysis	Value	Ultimate analysis (dry basis)	
			Value
Moisture PN-EN 15414-3:2011	7.1%	C	35.60 wt%
Volatiles PN-EN 15402:2011	60.7%	H	5.08 wt%
Ash PN-EN 15402:2011	34.9%	N	5.39wt%
HHV, MJ/kg	15.92 MJ/kg	S	1.93 wt%
		O ₂	17.10 wt%

3 Installation description

The process of gasification was carried out in a simple fixed bed gasifier. The reactor consists of an isolated electric heated quartz tube (length: 600 mm, inner diameter: 75 mm). Inside the quartz tube a steel basket was placed, where the sewage sludge sample was introduced. The reactor was equipped with four connectors: an inlet one, through which a gasifying agent was introduced and three outlets. The purpose of the three outlet connectors was to lead the producer gas into an extractor, connecting the gasifier with the plasma reactor and to allow sampling gas directly from the reactor. The plasma reactor was constructed for plasma gasification of plastic and organic wastes [34]. The reactor consists of three plasma generation branches, however, for the purpose of tar reduction experiment only one was in use. The plasma generation branch consists of 2 kW microwave generator, circulator, reflectometer and a waveguide. A picture of the plasma reactor (without the reflectometer) is shown in Fig. 1. The microwave plasma was generated in a 70 mm long quartz tube located in the reactor's plasma head with the use of tungsten rod. After being ignited, the plasma and all the gases, introduced into it, go through the main reactor's quartz tube at the end of which gaseous samples were taken. The path between the gasifier and the plasma reactor includes a three-necked bottle fed with water and the Dreschel bottle to cool the producer gas, separate the heaviest compounds and secure the pipelines and the plasma head from thermal damage and blocking by tar. A simplified scheme of the whole installation is presented in Fig. 2.

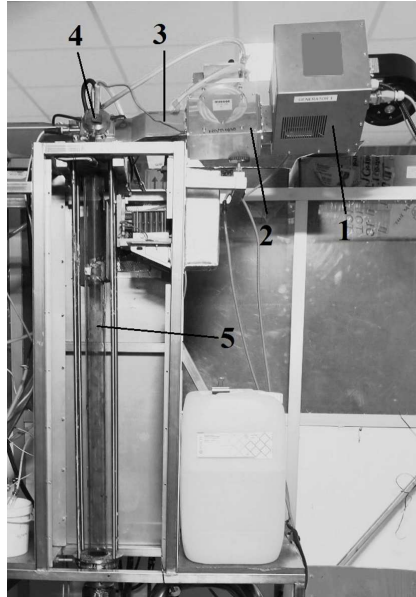


Figure 1: The microwave plasma reactor: 1 – microwave generator, 2 – circulator, 3 – waveguide, 4 – plasma head, 5 – quartz tube.

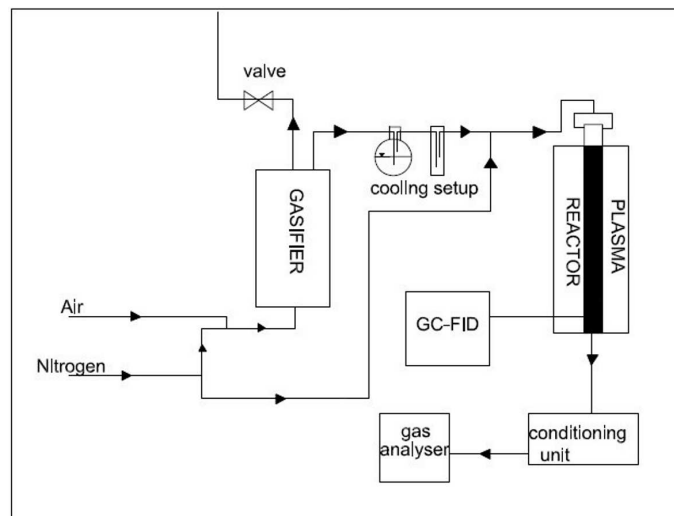


Figure 2: Scheme of the installation (GC-FID – gas chromatopography flame ionization detector).

4 Process conditions and analytical methodology

The first step in the experiment was to heat up the gasifier and its pipelines to prevent them from blocking by tar. After that, the basket was filled with 650 g of dried sewage sludge. Since the material was stored in a laboratory hall its water content was about 27.5%. The basket was introduced into the reactor heated up to 350 °C. At the same time, the reactor's temperature was set to 700 °C, a gasifying agent was introduced and a gas analyzer was turned on. At the temperature of 650 °C the plasma was ignited with a plasma agent (N₂) flow rate 1200 l/h. After reaching 700 °C the main valve of the gasifier was closed and the process gas was directed, through a cooling setup which consisted of two flasks, into the plasma reactor – at the same time the plasma agent flowrate was reduced.

During the experiment, many gas flow regimes were examined. Nevertheless, the purpose of these investigations was not focused on optimizing the gasification process. The main goal of this work was to examine the potential of microwave plasma as a method of gas cleaning. Thus, the selection of the gas flow was to:

- provide the gasification process long enough to take all the measurements necessary,
- ensure the gas compounds concentrations high enough to prove the microwave plasma efficiency,
- enable sufficiently stable plasma work,
- prevent plasma head, specifically the small quartz tube inside, from being overheated.

Three gas flow regimes were selected to be presented in this work. Considering gasifying agent, it was: a mixture of air and nitrogen: 900 l/h of air and 300 l/h of nitrogen; 1000 l/h air and 200 l/h of N₂; and air – 1000 l/h – without any addition of N₂. Since the plasma unit was designed to work with pure nitrogen/air, the stream of the producer gas had to be diluted with technical nitrogen from a steel bottle. Moreover, due to plasma reactor construction, which enables an easy measurement of an outlet gas flow, some simplifying steps were taken to determine the plasma reactor's inlet flow. A measurement of a cold gasifying agent stream at the outlet of the gasifier was measured along with the flow rate of the plasma agent nitrogen. These two streams were mixed at the inlet of the plasma reactor. That way, no measurement of the flow rate of the gas produced during gasification (gas derived directly from the sewage sludge gasification) was taken. Nevertheless, the flow rates of plasma agent mixtures, accordingly to the gasifying agent flows

given above, were as follows: 720 l/h of cold gasifying mixture and 1000 l/h of nitrogen; 550 l/h and 600 l/h N₂; and 450 l/h and 750 l/h N₂. All the flows were controlled with the use of rotameters at the temperature of 20 °C.

For the purpose of further sections of this paper, the cases with different gas flows will be labeled as follows: 720+1000/900+300, 550+600/1000+200, and 450+750/1000. In other words, the 720+1000/900+300 symbol means, that if the gasifying agent flow rates was 1200 l/h (900 l/h of air and 300 l/h of N₂), 720 l/h of this gas was introduced into the plasma reactor and additionally, the reactor was fed with 1000 l/h of N₂. Naturally, a real gas flow was higher due to the gas produced from the sewage sludge.

The gas analyzer, that was turned on at the temperature of 350 °C was the GAS 3000 (GEIT). It allowed measuring of all the gases typical for a producer gas: CO, CO₂, CH₄, and H₂. The analyzer worked online. Moreover, it allowed to record the time of individual steps of the experiment: beginning of the experiment (at 350 °C), moments when the gasifier reached temperature of 500, 550, 600, 650, and 700 °C, plasma ignition (at 650 °C), valve closing and introducing gas into the plasma (700 °C), taking the 1st and the 2nd gas samples and plasma extinguishing.

The samples from the experiment were taken approximately 1 min after the gas being introduced to the plasma reactor (1st sample) and after 5 min (2nd sample). The samples were taken directly during the process with the use of a gastight syringe and analyzed with the use of a gas chromatograph HP 6890 equipped with a flame ionization detector (FID) and a HP-5 column. The conditions for gas chromatopography (GC) analyses were dictated by the time of the processes. Since the authors wanted to take at least two samples during one experiment, the time of the analyses must have been limited. Thus, the first analysis last 4 min (in constant column temperature of 70 °C) and allowed to measure only lighter compounds. The second analysis last 9 min (4 min in 70 °C followed by an increase of the temperature to 120 °C with the rate of 30 °C). As a result, it provided detection of heavier compounds. Still, the column characteristic and limited time did not allow to detect 2-ring aromatics and heavier compounds. Hence, the analyses focused mainly on one ring aromatics: benzene and toluene. Those two compounds could have been identified qualitatively and quantitatively due to previous investigations [33]. Nevertheless, although the other compounds are expressed only as a peak surface, due to linear correlation between compound concentration and the chromatograph's response, it is still possible to estimate microwave plasma efficiency.

Additionally, to prove the presence of the tar species in the producer gas a sample of the gas was taken directly from the gasifier. The sample was introduced to the Tedlar bag, and analyzed in an external laboratory with the use of Perkin Elmer gas chromatopography–mass spectrometry (GC-MS) system.

5 Plasma stability of the microwave plasma source

While the plasma reactor fed with a pure nitrogen or air can work with no stability problems or malfunctions, introducing other compounds results in plasma extinguishing. This is probably not due to the tar compounds, since introducing even 0.015 kg of toluene per 1 m³ of nitrogen did not affected stability of the plasma [35]. The reason for plasma stability problems can be attributed to a relatively high concentration of hydrogen and light hydrocarbons like methane. A series of experiments was carried out to prove this hypothesis. While during normal plasma work, fed with pure nitrogen, the microwave power delivered to plasma was 1150±50 W and the reflection was only a few watts, introducing H₂ or CH₄ led to increase of the reflected power. This phenomenon is shown in Figs. 3a and 3b.

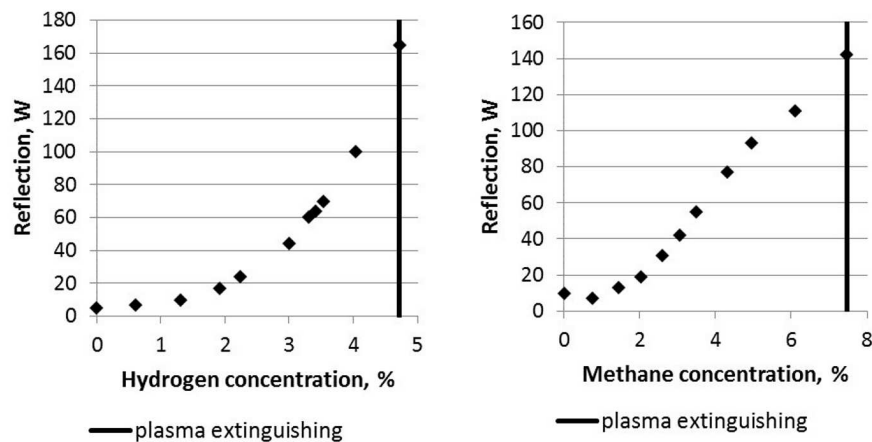


Figure 3: Correlation between hydrogen concentration and power reflection for gas flow rate 1200 l/h.

After reaching a certain concentration of the mentioned compounds, the plasma extinguished. This might be assigned to hydrogen and methane properties, more specifically, to their heat capacity and thermal conductivity. In case of H₂ these

parameters are higher even by one order of magnitude when compared to other gases like nitrogen. These properties led to cooling of the plasma, decreasing of its ionization and, as a result, increasing of reflection and finally extinguishing of the plasma [36]. Same phenomenon can be observed with an increasing plasma agent flow and by that, cooling the plasma. For example, when the plasma agent flow was on a level of 29 l/h it was impossible to avoid plasma extinguishing. At the same time, decreasing the flowrate to 1150 or 1200 l/h enabled to keep the reflection on the level that allowed sustaining the plasma – with time, the concentration of the producer gas compounds decreased and so the reflection did. It is important to mention, that even with decreased gas flows, it was not always possible to avoid plasma extinguishing. Moreover, in terms of heat transfer and plasma cooling, a radiation may also play an important role and be affected by the gas composition [37]. Finally, it was reported that the electropositive behavior of CH_4 may cause the fast reduction of electrons' energy and their concentration [38] (which is a function of plasma temperature). The same problems were indicated in a work of Jasiński *et al.* [33] – increasing methane concentration in a plasma agent gas led to stability problems. Similar obstacle in a plasma stable work, considering hydrogen addition, was mentioned in a work of Jankowski and Reszke [39]. To overcome this problem, it is recommended to increase microwave power or modified plasma reactor [33,39]. From these two options, the latter one seems to be more justified from the economic point of view.

6 Concentrations of CO , CO_2 , H_2 and CH_4

Figures 4 and 5 show changes of CO , CO_2 , H_2 , and CH_4 concentrations during the gasification process with and without use of the plasma reactor. In the case when no plasma was used, the process procedure was carried out exactly the same way as described in Sec. 4, but without plasma ignition. Beside the concentrations, the figures show temperature increase and previously mentioned steps of the process, i.e., plasma ignition, gas introduction, the first and the second sampling and plasma extinguishing. As it can be seen from comparison of the two figures, applying of plasma increased CO and H_2 concentration significantly. At the same time, CO_2 and CH_4 decreased. The same phenomenon can be observed in Fig. 5 after plasma being extinguished. These changes can be obviously assign to thermal cracking, steam reforming and other possible reactions shown in Tab. 2 [40]. Although presented reactions (Tab. 2) consider toluene, in fact they can be attributed to any other hydrocarbon.

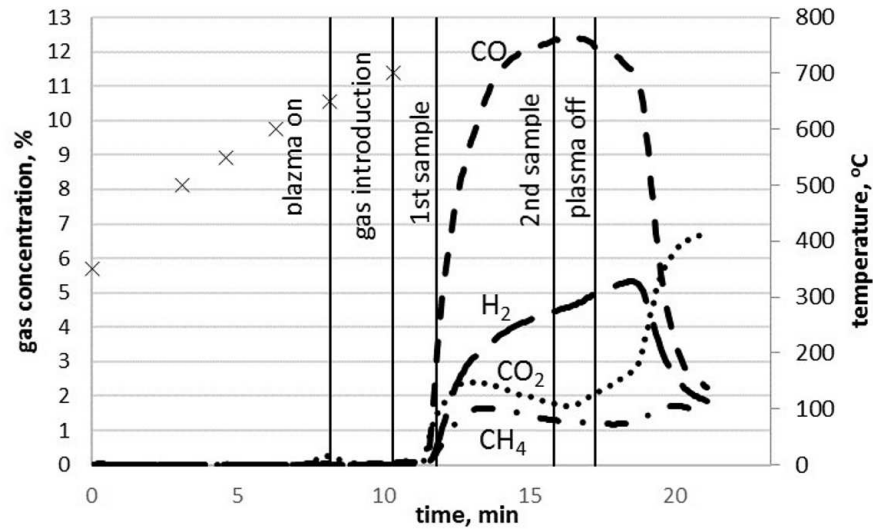


Figure 4: Subsequent process steps including gases concentrations. Plasma in use.

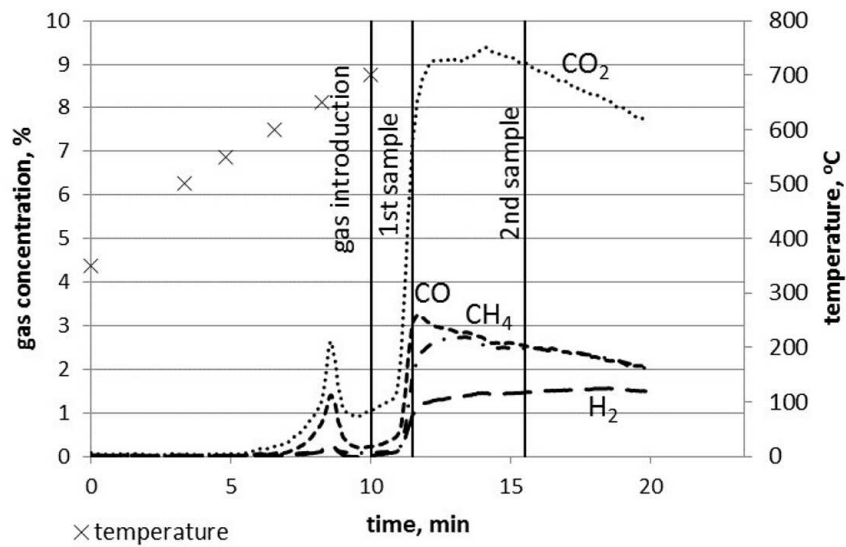


Figure 5: Subsequent the process steps including gases concentrations. No plasma applied.

Table 2: Possible hydrocarbon reactions with toluene as an example.

Process	Reaction	Eq. no.
Steam reforming	$C_7H_8+7H_2O \rightarrow 7CO+11H_2$	(1)
	$C_7H_8+14H_2O \rightarrow 7CO_2+18H_2$	(2)
Steam dealkylation	$C_7H_8+H_2O \rightarrow C_6H_6+CO+2H_2$	(3)
	$C_7H_8+2H_2O \rightarrow C_6H_6+CO_2+3H_2$	(4)
Hydrocracking	$C_7H_8+10H_2 \rightarrow 7CH_4$	(5)
Hydrodealkylation	$C_7H_8+H_2 \rightarrow C_6H_6+CH_4$	(6)
Dry reforming	$C_7H_8+7CO_2 \rightarrow 14CO+4H_2$	(7)
	$C_7H_8+11CO_2 \rightarrow 18CO+4H_2O$	(8)
Thermal cracking	$nC_7H_8 \rightarrow mC_xH_y+pH_2$	(9)
Carbon formation	$C_7H_8 \rightarrow 7C+4H_2$	(10)
Partial oxidation	$C_7H_8+5.5O_2 \rightarrow 7CO+4H_2O$	(11)

On the other hand, carbon dioxide reduction can follow two parallel pathways: boudouard reaction



carbon dioxide dissociation reaction



While the first reaction is typical for gasification processes, the second one is attributed to plasma medium since it requires high temperatures and is enhanced by the electrons presence [22].

A closer insight into the gases concentrations is given in Figs. 6 and 7. As the diagraphes demonstrate, in case when the plasma was used, CO concentration increased and CO₂ concentration decreased about four times (Fig. 6). At the same time, hydrogen concentration is about 2–3 times higher when results with plasma are compared to these without. Accordingly, methane concentration is about 1.5–2 times smaller.

While the presented figures concern the case study 450+750/1000, results obtain in the remaining experiments were very similar. They are presented in Tab. 3. A significant difference in concentrations can be noted for the case

720+1000/300+900. This can be explained by a higher gas flow, which firstly, cools down the plasma, and secondly, results in a shorter reaction time.

Table 3: Plasma influence on gases concentration in three gas flow regimes.

Flow rate, l/h	Plasma	CO	CO ₂	CH ₄	H ₂
450+750*	No	2.68%	9.06%	2.55%	1.42%
1000**	Yes	11.27%	2.06%	1.41%	3.93%
550+600*	No	2.79%	7.27%	2.44%	1.12%
1000+200**	Yes	13.65%	1.16%	1.22%	4.86%
720+1000*	No	1.82%	7.08%	1.58%	1.29%
900+300**	Yes	7.40%	2.44%	0.62%	2.47%

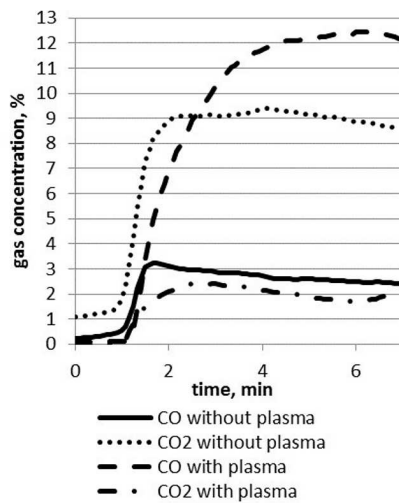


Figure 6: Changes in the concentration of CO and CO₂ with and without use of plasma.

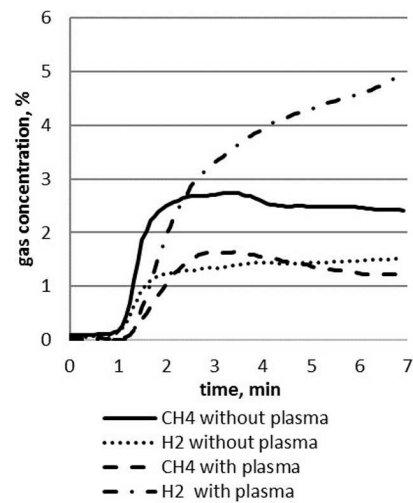


Figure 7: Changes in the concentration of H₂ and CH₄ with and without use of plasma.

7 Tar and organic components

As it was mentioned before, to prove the presence of the tar compounds in the process gas, the additional chemical analysis was done. Results of this analysis are presented in Fig. 8. The analysis was carried out on a pure – not diluted – producer gas with a use of GC-MS. Table 4 presents the highest values obtained with a high probability of the peak's correct identification.

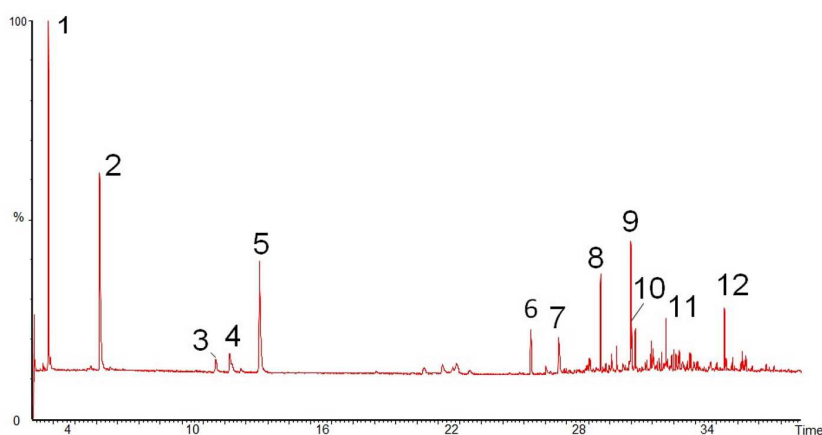


Figure 8: Chromatogram obtained due to GC-MS analysis of the producer gas. For legend see Tab. 4.

Mass spectroscopy analysis proved that the producer gas contains one-, two-, and three-ring aromatics and heterocyclic compounds. Moreover, the chromatogram (Fig. 8) shows that the dominating aromatic compounds were benzene, toluene and, in smaller amounts, styrene, naphthalene and cresol.

Tar species are condensable, thus, it seems necessary to conduct any analyses with them as quick as possible. Hence, further analyses were carried out with a use of GC-FID located near the gasifier and plasma reactors. Due to GC-FID and its column characteristic, the most detailed analysis and results concerned benzene and toluene.

The chromatogram in Fig. 9 presents a mirror reflection of two gas samples: the upper one when the plasma was applied and the lower without the plasma. It is clearly seen, that an application of the plasma led to a significant drop in light hydrocarbons (represented by the first few peaks before benzene's peak) and benzene amounts. An even higher conversion can be noticed in case of toluene and heavier species. More detailed results are given in Tab. 8.

Table 4: Tar compounds identified with the use of GC-MS.

No.	Compound name
1	benzene
2	toluene
3	ethylbenzene
4	1,3-dimethylbenzene
5	styrene
6	indene
7	p-cresol
8	naphthalene
9	indole
10	1-methylnaphthalene
11	acenaphthylene
12	anthracene

The table includes all the peaks values that were registered by the GC-FID. The table presents two samples taken in 4 min interval. Although the 2nd sample analysis last longer, it is clearly noticeable that there are more species detected in the second case. It is shown by the amount of species being placed between benzene (retention time 1.840–1.841 min) and the peak emerging at retention time 3.664–3.665 min, which must be with a high probability a styrene. Moreover, the concentrations, expressed as peak surface in picoampere-seconds (pA s), of toluene and styrene are higher in the second sample as well. These differences can be explained by the gasification process dynamics. Although the sampling procedure started after the temperature reached 700 °C, it is important to notice that this was a measurement taken in a specific point near the wall of the reactor, thus, the temperature of the sewage sludge could have been lower – especially inside the material. Hence, sample taken 4 min later could have been assigned with a different, higher temperature inside the processed material. However it is well known that the tar species are generated in higher temperatures [41] – that could have resulted in the higher concentrations of the previously mentioned compounds.

Tables 5–7 give an insight into the microwave plasma efficiency in hydrocarbons/tar decomposition for the three gas flow regimes. The analyzed hydrocarbons were divided into five groups. The first one, labeled as ‘C1-C2’, includes methane and hydrocarbons with two carbon atoms in their structure – in the chromatogram (Fig. 9) these compounds were detected as a one peak. Next group consists of all the peaks between the first one and the one that corresponds to benzene, it is labeled as ‘C2<x<benzene’. The third and the fourth groups are benzene and toluene, accordingly. The last group includes all the peaks that were detected after the benzene, it is tapped as ‘>benzene’. Most of the concentrations presented in the tables are expressed as a peak’s surface, however, benzene and toluene, due to previous research [35], are additionally given in g/Nm³.

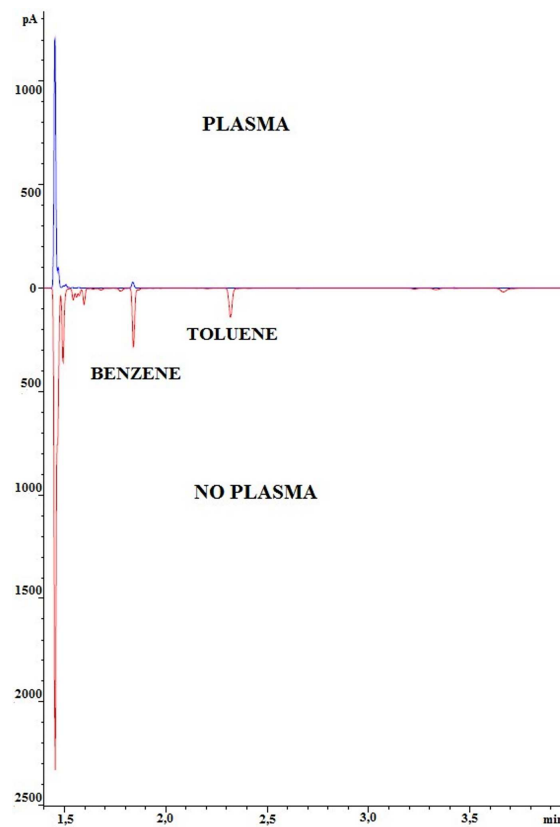


Figure 9: Chromatograms obtained from the 1st sample in case 450+750/1000.

Table 5: Peaks detected with a use of GC-FID in case 450+750/1000, t_r – retention time, S – peak's surface.

1st sample				2nd sample			
without plasma		with plasma		without plasma		with plasma	
t_r , min	S , pA s	t_r , min	S , pA s	t_r , min	S , pA s	t_r , min	S , pA s
1.454	2117.4	1.453	820.4	1.453	1683.8	1.451	787.2
1.493	218.5	1.506	19.3	1.492	172.5	1.504	14.9
1.544	98.8	1.570	2.0	1.542	170.0	1.568	1.7
1.597	59.8	1.837	23.2	1.571	48.2	1.835	35.7
1.641	7.2			1.596	47.9	8.508	7.8
1.68	13.2			1.639	19.8		
1.777	19.5			1.677	21.6		
1.841	237.7			1.724	5.1		
1.901	4.4			1.783	24.8		
2.203	3.7			1.840	215.2		
2.319	155.7			2.049	1.9		
3.228	7.4			2.077	2.5		
3.333	14.0			2.198	38.3		
3.665	42.6			2.318	183.4		
				2.408	3.2		
				2.719	5.5		
				2.891	3.7		
				3.004	2.2		
				3.226	11.8		
				3.331	25.0		
				3.428	4.5		
				3.664	90.5		
				5.264	7.0		
				5.313	6.2		
				5.466	11.4		
				5.52	11.6		
				6.258	21.1		
				8.522	17.8		

Table 6: Microwave plasma efficiency, case 450+750/1000.

Sample	Plasma	C1-C2, pA s	C2<x<benzene, pA s	Benzene, pA s (g/Nm ³)	Toluene, pA s (g/Nm ³)	>benzene, pA s
1st	No	2117.4	417.1	237.7 (4.37)	155.7 (3.16)	227,9
	Yes	820.4	21.3	23.2 (0.43)	n/a	n/a
Conversion		61.25%	94.89%	90.24%	100%	100%
2nd	No	1683.8	509.8	215.2 (3.96)	183.4 (3.72)	447.8
	Yes	787.2	16.6	35.7 (0.66)	n/a	7.8
Conversion		53.25%	96.74%	83.41%	100%	98.27%

Table 7: Microwave plasma efficiency, case 550+600/1000+200.

Sample	Plasma	C1-C2, pA s	C2<x<benzene, pA s	Benzene, pA s (g/Nm ³)	Toluene, pA s (g/Nm ³)	>benzene, pA s
1st	No	2168.4	565.6	211.6 (3.89)	178.6 (3.63)	266.4
	Yes	1369.1	36.4	81.1 (1.49)	7.8 (0.16)	16.5
Conversion		36.86%	93.75%	61.68%	95.66%	93.81%
2nd	No	2043.0	648.1	241.2 (4.44)	241.3 (4.90)	606.3
	Yes	555.5	7.8	20.8 (0.38)	n/a	16.0
Conversion		78.21%	98.80%	91.38%	100%	97.36%

Table 8: Microwave plasma efficiency, case 720+1000/900+300.

Sample	Plasma	C1-C2, pA s	C2<x<benzene, pA s	Benzene, pA s (g/Nm ³)	Toluene, pA s (g/Nm ³)	>benzene, pA s
1st	No	1314.5	311.3	145.8 (2.68)	103.9 (2.11)	150,0
	Yes	551.0	14.5	49.8 (0.92)	5.7 (0.12)	8.2
Conversion		58.08%	95.36%	65.86%	94.54%	94.56%
2nd	No	1026.8	309.5	126.9 (2.33)	111.3 (2.26)	330.5
	Yes	334.7	12.7	42.0 (0.77)	5.7 (0.12)	30,4
Conversion		67.40%	95.89%	66.90%	94.87%	90.80%

Usually the correlation between a gas concentration and a chromatograph response – expressed as a peak surface in pA s – are in linear correlation (what was proved to be correct in case of benzene and toluene [35]), therefore the microwave plasma efficiency can be simply estimated with a following relation:

$$\text{relation of decomposition efficiency} \quad \eta = \frac{C - C_p}{C} \times 100\% , \quad (14)$$

where: C – concentration measured when no plasma is applied, expressed in g/m^3 or pA s, C_p – concentration measured when plasma is applied, expressed in g/m^3 or pA s.

The data collected in the tables show again that the sample gathered 4 min later than the 1st one includes greater amounts of heavier species and lower concentrations of benzene and lighter compounds. What most important, the data presents efficiency of these species conversion. The highest conversion can be assigned to toluene and groups labeled as ‘C2<x<benzene’ and ‘>benzene’. Within these groups, the decomposition efficiency exceeded 90% in all the cases. If the ‘n/a’ is given in the table, it means that no species from the group was detected. However, it does not have to mean that there were no particles of that compound. It only means, that the concentration was below the GC’s sensitivity, nonetheless, it response to concentrations below $10 \text{ mg}/\text{Nm}^3$.

A lower efficiency can be attributed to ‘C1-C2’ and benzene. In the first case, the conversion is on a level of about 60% varying from 36.86% to 78.21%. When the benzene is considered, the decomposition efficiency varies from 61.68% to 91.38% depending on the case and sample. Generally, this drop in efficiency, in comparison to the other groups results, from the fact that benzene and C1, C2 hydrocarbons are products of other compounds conversion (see Eqs. (3)–(6) and (9). While the cases 450+750/1000 and 550+600/1000+200 gave similar results, the case 720+1000/900+300 showed a bit worse efficiency. As it was mentioned in Sec. 2.3, this phenomenon is a result of higher gas flow.

Finally, it is worth to mention, that the presented results were obtained on the basic of two samples taken during one experiment per case. Moreover, the experiments with and without plasma were carried out in separate runs, thus, they might have been slightly different in terms of conditions, gas composition and timing. Additionally, the sewage sludge is rather an inhomogeneous material, thus, its properties may vary with each sample taken. Nevertheless, obtained results show clear tendencies making them sufficiently reliable to prove the microwave plasma efficiency in the producer gas cleaning.

8 Conclusion

Presented work proves a high potential of the microwave plasma as a method of gas cleaning and tar decomposition. The results showed, that using this method enabled to reduce toluene's concentration from 4.90 g/Nm³ to a level below 10 mg/Nm³. In case of other one-ring aromatics the efficiency of conversion was at similar level and it exceeded 90%. Furthermore, applying the plasma source resulted in a significant improvement in the producer gas quality. It not only allowed increasing the concentrations of CO and H₂, but additionally led to a considerable drop in the CO₂ concentrations.

The major obstacle experienced during the research was the plasma stability. Further research should include modification of the plasma reactor making possible to operate with a high concentration of the producer gas. Moreover, some further research considering heavier species, like two-ring aromatics, are advisable.

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