Soot and Char Formation in the Gasification of Pig Manure in a Drop Tube Reactor

I. Adánez-Rubio¹,²,³*, R. Ferreira², T. Rio², M. U. Alzueta¹, M. Costa²

¹Aragón Institute of Engineering Research (I3A), Department of Chemical and Environmental Engineering, University of Zaragoza, Zaragoza 50018, Spain

²IDMEC, Mechanical Engineering Department, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal

³Instituto de Carboquímica (ICB-CSIC), Department of Energy and Environment, Miguel Luesma Castán 4, 50018, Zaragoza, Spain

*Corresponding author: Phone: +34976733977, e-mail address: iadanez@icb.csic.es
Abstract

Biomass gasification offers a significant potential to close the loop of agriculture and many other activities that produce biomass residues. Pig manure, a residue produced in farms, has a huge pollutant potential due to its high production and chemical characteristics. It is necessary to take some control measures to decrease it, being pig manure gasification an interesting option. The present work studies the impact of the gasification temperature and atmosphere on the syngas composition (CO, H\textsubscript{2}, CH\textsubscript{4} and CO\textsubscript{2}) and formation of soot and char in the gasification of pig manure in a drop tube furnace. The temperature varied between 900 and 1200 ºC, and the gasification atmospheres included mixtures of O\textsubscript{2}/N\textsubscript{2}, O\textsubscript{2}/CO\textsubscript{2}/N\textsubscript{2} and O\textsubscript{2}/H\textsubscript{2}O/N\textsubscript{2}. The results revealed that i) the syngas H\textsubscript{2}/CO ratio and its low heating value increase as the gasification temperature increases regardless of the gasification atmosphere; ii) the addition of H\textsubscript{2}O to the O\textsubscript{2}/N\textsubscript{2} gasification atmosphere augments significantly the syngas H\textsubscript{2}/CO ratio, but does not enhance its low heating value, while the addition of CO\textsubscript{2} increases slightly the H\textsubscript{2}/CO ratio, but significantly the heating value, iii) for the present reactor, the optimum operating conditions for the gasification of the pig manure in terms of syngas heating value and yield are a gasification temperature of 1200 ºC and a gasification atmosphere composed of a mixture of O\textsubscript{2}/CO\textsubscript{2}/N\textsubscript{2}; and iv) soot yields increase as the temperature increases when gasification occurs in the O\textsubscript{2}/N\textsubscript{2} and O\textsubscript{2}/CO\textsubscript{2}/N\textsubscript{2} environments, remaining almost constant in the O\textsubscript{2}/H\textsubscript{2}O/N\textsubscript{2} environment.

Keywords: Gasification, pig manure, temperature, atmosphere, syngas, soot, char.
1. Introduction

Gasification is a thermochemical process that produces syngas from solid fuels. The syngas is then used to produce highly valuable chemicals, gaseous fuels or power [1]. Nowadays, the gasification process is responsible for 30% of the methanol world production and 25% of ammonia [2], being the chemical production the main target of this process. The process of gasification can be carried out in different atmospheres, e.g. O$_2$, depleted air, CO$_2$, steam or mixtures of these compounds. The process usually occurs at high temperature and pressure in order to maximize the CO and H$_2$ production, while reducing the production of undesirable products such as tars.

The use of different types of biomass in the gasification process has augmented in recent years as a way of reducing the dependence of fossil fuels. Moreover, biomass fuel is generally considered as carbon neutral on the assumption that it is replaced by capturing the released CO$_2$ [3-5].

The use of biomass residues, e.g. pig manure, in processes of gasification helps to control the huge quantities of the liquid and solid residues generated nowadays and thereby to reduce the energy needs. Pig manure is a biomass residue composed by liquid and solid excrements. Its composition depends on several factors, but in general is a residue with a high biological oxygen demand (13400-40000 mg O$_2$/dm$^3$) and a high macronutrients content, mainly nitrogen (3000-5200 mg/dm$^3$) and phosphorous (660-920 mg/dm$^3$) [6]. The production of pig manure amounts to millions of ton only in European Union (EU) [7]. Due to the main characteristics of this residue there is a need to manage it properly avoiding environmental problems, such as nitrogen emissions to the atmosphere, water contamination by nitrates or water eutrophication. Currently, this biomass residue is mainly used as soil amendment in
agriculture, which can be considered environmentally sustainable only if there is enough land available near the generation point. Gasification, together with pyrolysis and anaerobic digestion, are being studied as alternatives for the management of pig manure since these processes produce valuable products such as syngas, chemicals or energy [8-10].

The gasification process, however, produces undesirable solid carbonaceous particles, such as soot, that decrease the carbon conversion efficiency, and that can also create problems downstream, such as the deterioration of the equipment performance and durability, formation of dark exhaust plumes or agglomeration of soot in the walls [11]. In addition, the very small soot particles can affect the human health, in particular they can infiltrate in cardiovascular and respiratory system, leading to lung malfunction [12].

There are several factors that affect the gasification process, namely the gasification atmosphere and temperature and the type of reactor [13-18]. Gasification atmospheres can be composed by air, oxygen, dioxide carbon or steam, or mixtures of these compounds. Operation with air leads to a syngas with a low heating value due to the presence of nitrogen. The use of oxygen has the advantage of increasing the calorific value of the syngas, but the need of an air separation unit makes the process more expensive [1]. Gasification using carbon dioxide as the gasifying agent increases the formation of CO, but reduces the production of H$_2$ [13]. Finally, the utilization of steam promotes the water-gas shift reaction, generating a syngas with more H$_2$ [14-16], thereby increasing the heating value of the syngas, while reducing tars through the decomposition of the organic pyrolytic vapors. The gasification temperature can affect the syngas, tar and char yields. Higher temperatures lead to greater amounts of gas produced, but lower amounts of tar and char. Furthermore, higher temperatures also promote the formation of H$_2$, while decreasing the formation of CO and
light hydrocarbons [17, 18]. Reactors used in gasification processes include fixed or moving beds, fluidized beds, entrained flow and drop tube reactors. Entrained flow [19, 20] and drop tube reactors [21, 22] are commonly used to study the gasification of biomass residues under well controlled conditions (particle size, temperature, residence time, …).

In recent years interest on manure gasification has increased significantly due to the opportunity to drastically reduce CO$_2$ emissions and recycle efficiently nutrients [23, 24], with studies including gasification of manures from different animals [25-29], co-gasification of manure with other biomass residues [30] and pyrolysis of manure followed by gasification of the char formed [31]. Hussein et al. [26] studied the effects of temperature, gasifying media and oxygen addition on the gasification of chicken manure in a lab-scale semi-batch reactor. The authors observed that the energy yield increases with the temperature, being the highest yield obtained when using CO$_2$ as the gasifying media, followed by steam [26]. Moreover, the authors found that the addition of O$_2$ decreases significantly the gasification reaction time and the energy yield [27]. Madadian et al. [24] studied the gasification of six different biomass residues, including chicken manure, in a research-scale down-draft reactor using depleted air as the gasification agent. They found that the CO and H$_2$ concentrations in the syngas increase with the temperature, while the CO$_2$ concentration decreases.

The literature survey reveals, however, that systematic and detailed studies on the gasification of pig manure are rare. In this context, the aim of this work is to examine the impact of the gasification temperature (900 to 1200 °C) and atmosphere (O$_2$/N$_2$, O$_2$/CO$_2$/N$_2$ and O$_2$/H$_2$O/N$_2$) on the syngas composition (CO, H$_2$, CH$_4$ and CO$_2$) and formation of soot and char in the gasification of pig manure in a drop tube reactor (DTR).
2. Materials and Methods

The biomass residue used in all gasification tests was pig was non-digested sun dried pig manure stored outdoors (O0°12'39.53", N40°56'14.03") at ambient conditions during several months. For this work, the pig manure was crushed and sieved to sizes between 100 and 150 µm with the aid of a SS-15 Gilson Economy 203 mm Sieve Shaker. Table 1 shows the main chemical properties of the biomass used. For the proximate and ultimate analysis of the solid samples, the following standard methods have been used: UNE-EN ISO 18134-3:2016 for moisture, UNE-EN ISO 18122:2016 for ashes, UNE-EN ISO 18123:2016 for volatile matter, UNE-EN ISO 16948:2015 for ultimate analysis, and UNE-EN ISO 18125:2018 for heating value. Before each test, the particles were dried in an oven at 105 °C to remove moisture.

Table 1. Chemical properties of the pig manure.

<table>
<thead>
<tr>
<th>Proximate analysis (wt.%, as received)</th>
<th>Ultimate analysis (wt.%, as received)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>Carbon</td>
</tr>
<tr>
<td>17.80 ± 0.4</td>
<td>24.09 ± 0.8</td>
</tr>
<tr>
<td>Ash</td>
<td>Hydrogen</td>
</tr>
<tr>
<td>33.74 ± 0.2</td>
<td>2.57 ± 0.1</td>
</tr>
<tr>
<td>Volatile matter</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>42.71 ± 0.4</td>
<td>2.62 ± 0.1</td>
</tr>
<tr>
<td>Fixed carbon</td>
<td>Sulphur</td>
</tr>
<tr>
<td>5.75 ± 0.3</td>
<td>0.80 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>Oxygen</td>
</tr>
<tr>
<td></td>
<td>18.38 ± 1</td>
</tr>
</tbody>
</table>

Low heating value (MJ/kg) 9.36 ± 0.1

Figure 1 shows a schematic of the experimental setup used in this work for the gasification experiments. It comprises a biomass feeder, a gas supply system, for O2, CO2 and N2, a vertical electrically heated DTR, a particle collection system and a gas sampling and analysis system. The biomass feeder consists of a twin-screw volumetric feed where the biomass is poured. The biomass particles are carried to a water-cooled injector with the aid of a carrier.
gas, N\textsubscript{2} in this case. This injector feeds the particles (and the carrier gas) into a vertical nonporous mullite tube within the electrically heated DTR. The mullite tube has a total length of 1750 mm and an inner diameter of 40 mm, and its wall temperatures are continuously monitored by three type-K thermocouples uniformly distributed along the tube. The wall temperature can be varied up to 1300 °C and particles injected from the top of the DTR typically experience heating rates of ~10\textsuperscript{5} K/s. A concentric passage between the mullite tube and the injector ensures the introduction of the gasifying agent stream, a mixture of N\textsubscript{2}, O\textsubscript{2} and steam, or CO\textsubscript{2}, into the tube of the DTR. The steam is generated by an evaporator at a pressure of 2 bar. The remaining gases are supplied from pressurized bottles. At the bottom of the reactor is located the particle collection system. This system is composed of two cyclones, an in-house made cyclone and a commercial cyclone (Dekati®), and a low pressure 13-stage cascade impactor (DLPI, Dekati® Ltd.). To avoid gas condensation during the experiments, the particle collection system was maintained at temperatures above 150 °C using heating blankets. The two cyclones were able to capture particles (char) with sizes above 10 µm, while the 13-stage cascade impactor was able to capture particles (soot and char) with sizes below 10 µm. The particles retained in the 13-stage cascade impactor were identified as soot and char using two methods: scanning electron microscopy/energy dispersive X-ray spectroscopy (SEM/EDS) and ultimate analysis of the samples. The syngas composition was measured using a paramagnetic pressure analyzer for O\textsubscript{2}, a non-dispersive infrared analyzer for CO\textsubscript{2} and CO and a gas chromatograph Clarus 500 for the remaining gases reported.
Figure 1: Schematic of the experimental setup used in this work for the gasification experiments.

The temperature during the gasification experiments was varied between 900 and 1200 ºC. Three distinct gasification atmospheres were used: O₂/N₂, O₂/CO₂/N₂ and O₂/H₂O/N₂. The biomass feed rate was constant and equal to 30 g/h. The oxygen ratio, λ, defined as the ratio between the oxygen fed and the stoichiometric oxygen for the biomass combustion, was also kept constant for all experiments and equal to 0.6. The particles residence times in the DTF were estimated to be 2-3 seconds. The inlet concentrations of both CO₂ and H₂O were also kept constant (5 vol.%). The total inlet gas flow was 10 dm³/min, being N₂ used to balance.
In this work, the following parameters were used to evaluate the efficiency of the gasification process. The cold gas efficiency ($CGE$), defined as the ratio between the chemical energy leaving the reactor in the syngas and the chemical energy entering the reactor in the biomass, is calculated as:

$$CGE = \frac{Q_{\text{syngas}} \cdot LHV_{\text{syngas}}}{m_{\text{bio}} \cdot LHV_{\text{bio}}}$$  \hspace{1cm} (1)$$

where $LHV_{\text{syngas}}$ and $LHV_{\text{bio}}$ are the low heating values of the syngas and biomass, respectively.

The carbon conversion efficiency ($CCE$) to syngas, defined as the ratio between the carbon leaving the gasifier as syngas and the carbon entering the gasifier, is calculated as:

$$CCE = \frac{Q_{\text{syngas}} \cdot \sum_{i} y_{\text{carbon}i} \cdot x_{\text{carbon}i}}{m_{\text{bio}} \cdot y_{\text{carbon}}}$$  \hspace{1cm} (2)$$

where $Q_{\text{syngas}}$ is the syngas flow rate (in Nm$^3$/h), $x_{\text{carbon}}$ is the molar fraction of carbon in the products, which includes carbon in CO, CO$_2$ and CH$_4$. The experiments carried out with CO$_2$ as gasification agent, only the CO$_2$ produced in the pig manure gasification was used to calculate CCE. $m_{\text{bio}}$ is the feeding mass rate of the biomass (in kg/h) and $y_{\text{carbon}}$ is the carbon mass fraction from the ultimate analysis of the biomass.

The syngas yield ($\gamma_{\text{syngas}}$), defined as the amount of H$_2$ and CO generated during the process of gasification (mol syngas/kg biomass), is calculated as:

$$\gamma_{\text{syngas}} = \frac{Q_{\text{syngas}} \cdot y_{\text{CO}} + Q_{\text{syngas}} \cdot y_{\text{H}_2}}{m_{\text{bio}}}$$  \hspace{1cm} (3)$$

where $Q_{\text{syngas}}$ is the syngas flow rate (in Nm$^3$/h), $y_{i}$ is the gas molar fraction of CO and H$_2$, and $m_{\text{bio}}$ is the feeding mass rate of the biomass (in kg/h).
3. Results and Discussion

3.1 Syngas

Figure 2 shows the main syngas components (CO, H$_2$, CH$_4$ and CO$_2$) as a function of the gasification temperature for the three distinct gasification atmospheres. It is seen that the effect of the temperature on the CO production (Fig. 2a) depends on the gasification agent. In the case of the O$_2$/N$_2$ environment, the impact of the temperature is marginal, and in the cases of the O$_2$/CO$_2$/N$_2$ and O$_2$/H$_2$O/N$_2$ atmospheres, the behaviour is opposite. Using O$_2$/CO$_2$/N$_2$ as gasification agent, the production of CO increases from 45 to 55 vol. % when the gasification temperature increases from 900 to 1200 ºC but using O$_2$/H$_2$O/N$_2$ as gasification agent, the CO production decreases from 41 to 34 vol.% in the same temperature interval.

In the case of the H$_2$ (Fig. 2b), it is observed that its production increases as the temperature increases regardless of the gasification atmosphere. Moreover, the lower levels of H$_2$ are obtained with the O$_2$/N$_2$ gasification atmosphere, being the H$_2$ levels higher when using O$_2$/H$_2$O/N$_2$ as gasification agent.

Figure 2c reveals that the production of CH$_4$ during the gasification in the O$_2$/N$_2$ and O$_2$/H$_2$O/N$_2$ atmospheres remains nearly constant as the temperature increases, but it tends to increase in the O$_2$/CO$_2$/N$_2$ atmosphere. The CO$_2$ production (Fig. 2d) decreases with the temperature regardless of the gasification atmosphere, being this decrease more pronounced in the O$_2$/CO$_2$/N$_2$ atmosphere.
Figure 2. Main syngas components as a function of the gasification temperature for the three distinct gasification atmospheres. (a) CO, (b) H₂, (c) CH₄ and (d) CO₂. Data reported in nitrogen free basis.

The results have the same tendency has reported in literature. Madadian et al. [28] studied the gasification of six different types of biomasses, chicken manure among them, in the temperature interval of 600-1000 °C with λ between 0.1 to 0.5. They found that the CO produced had a maximum at 800°C, and the CO₂ produced had a minimum at 700 °C. However, in general for 5 of the 6 biomasses studied, the CO concentration increased with the temperature of gasification, while the CO₂ decreased. H₂ concentration was found to increase with the temperature for all the biomasses.
On the other hand, Hussein et al. [26] studied the gasification and pyrolysis of chicken manure. The gasification tests were done with air, \( \text{O}_2/\text{CO}_2/\text{N}_2 \) and \( \text{O}_2/\text{H}_2\text{O}/\text{N}_2 \). They found that the higher CO production was obtained with CO\(_2\) as gasification agent, and that the increase of the gasification temperature (from 600 to 1000 °C) increases the amount of CO produced. The H\(_2\) production increased with the temperature, obtaining the maximum value at 1000 °C, using steam as gasification agent.

Figure 3 shows the syngas H\(_2\)/CO ratio and \( LHV \) as a function of the gasification temperature for the three distinct gasification atmospheres. It is verified that both the H\(_2\)/CO ratio and the \( LHV \) increase as the gasification temperature increases regardless of the gasification atmosphere, being the lower values of both parameters associated with the gasification in the \( \text{O}_2/\text{N}_2 \) environment. The results obtained by Madadian et al. [28] for the chicken manure gasification with air (\( \lambda \) between 0.1 to 0.5) follow the same tendency as that of the present work, obtaining a maximum of H\(_2\)/CO ratio of 0.85 at 1000°C.

It is seen that the H\(_2\)/CO ratios are always lower than 1; therefore, the present syngas cannot be directly used in a Fischer-Tropsch process, which requires H\(_2\)/CO ratios between 2 and 3 [32-34]. The present syngas is, however, suitable for processes such as the synthesis of long chain hydrocarbons, where the H\(_2\)/CO ratios needed are lower (between 0.25 and 0.9), and there is also a need for CO\(_2\) [32-34].

The observed increase of the syngas \( LHV \) (cf. Fig. 3b) is mainly due to the increase in the H\(_2\) concentration in the syngas (cf. Fig. 2b). Moreover, the syngas with maxima \( LHVs \) is obtained when the gasification agent is \( \text{O}_2/\text{CO}_2/\text{N}_2 \), because this condition leads to the higher concentrations of CO and CH\(_4\) (cf. Figs. 3a and 3c). The \( LHV \) of the syngas produced in the
O₂/N₂ and O₂/H₂O/N₂ gasification atmospheres are rather similar. This means that the inclusion of steam in the gasification agent did not improve the syngas LHV, in contrast with the inclusion of CO₂.

**Figure 3.** Syngas characteristics as a function of the gasification temperature for the three distinct gasification atmospheres. (a) H₂/CO ratio and (b) LHV.

Figure 4 shows the parameters CGE (cold gas efficiency) and CCE (carbon conversion efficiency) as a function of the gasification temperature for the three distinct gasification atmospheres. It is seen that CGE, Fig. 4a, increases as the temperature increases regardless of the gasification atmosphere. The lower CGE values are obtained for gasification in the O₂/N₂ atmosphere, with values of 38% at 900 °C and 58% at 1200 °C, while the higher values are obtained in the O₂/CO₂/N₂ atmosphere, 43% at 900 °C and 88% at 1200 °C, which is generally consistent with the data shown in Fig. 3b. Similar results were, in general, obtained by Hussein et al. [26] in their chicken manure gasification study, even though for the maximum temperature analysed, the use of both CO₂ and steam were found to improve the syngas CGE value.
Figure 4b shows that CCE also tends to increase as the temperature increases for the three gasification atmospheres. The CCE values vary from around 70% for gasification in the \( \text{O}_2/\text{CO}_2 \) atmosphere at 900 ºC up to 95% in the \( \text{O}_2/\text{H}_2\text{O}/\text{N}_2 \) atmosphere at 1200 ºC. Hussein et al. [26] observed a similar trend for the chicken manure gasification between 600 to 1000 ºC: at the maximum temperature, they observed a CCE higher than 95% for the gasification with \( \text{CO}_2 \), air and steam, and a CGE of 75% for the pyrolysis conditions.

Figure 4. CGE (a) and CCE (b) as a function of the gasification temperature for the three distinct gasification atmospheres.

Figure 5 shows the syngas yield (\( \gamma_{\text{syngas}} \)) as a function of the gasification temperature for the three distinct gasification atmospheres. It is observed that the syngas yield increases with the temperature regardless of the gasification atmosphere. It is clear that the \( \text{O}_2/\text{CO}_2/\text{N}_2 \) and \( \text{O}_2/\text{H}_2\text{O}/\text{N}_2 \) gasification atmospheres lead to higher syngas yields than the \( \text{O}_2/\text{N}_2 \) gasification atmospheres, with the differences increasing with the temperature. The syngas yields vary from around 10 mol/kg of pig manure for gasification in the \( \text{O}_2/\text{N}_2 \) atmosphere at 900 ºC up to 22 mol/kg of pig manure in the \( \text{O}_2/\text{CO}_2/\text{N}_2 \) atmosphere at 1200 ºC.
From the discussion above, in regard to the $LHV$, $CGE$ and syngas yield, it can be concluded that the best operating conditions for the gasification of the pig manure in the present DTR are a gasification temperature of 1200 °C and a gasification atmosphere composed of a mixture of $O_2/CO_2/N_2$. Gasification of the pig manure in the $O_2/H_2O/N_2$ atmosphere, however, maximizes the $H_2/CO$ ratio and $CCE$.

### 3.2 Soot and char

As discussed earlier, two methods were used to distinguish between soot and char particles: SEM/EDS and ultimate analysis of the samples collected in the cyclones and 13-stage impactor. Fig. 6 shows typical SEM images of particulate matter collected in the in-house made cyclone and in the stages 5 and 13 of the impactor. The inspection of the SEM images
revealed the existence of char particles with diameters > 10 µm in the two cyclones and with diameters between 0.95 and 10 µm in stages 8 to 13 of the impactor, and the presence of soot particles with diameters < 0.6 µm in stages 1 to 7 of the impactor. Consistently, the EDS analysis (not shown) indicated relatively low percentages of carbon in the particulate matter collected in the two cyclones (between 18 and 25 wt.%) and in stages 8 to 13 of the impactor (between 15 and 21 wt.%), and relatively high percentages of carbon in stages 1 to 7 of the impactor (above 83 wt.%).

Figure 6. SEM images of particulate matter collected in the in-house made cyclone (a), in stage 13 of the impactor (b), and in stage 5 of the impactor (c), all for 1000 ºC and O_2/H_2O/N_2.

Ultimate analysis for all samples collected in the two cyclones were performed. Fig. 7 shows the percentage of organic matter and ash in the particulate matter collected in the two cyclones during the experiments as a function of the gasification temperature for the three distinct gasification atmospheres. It is seen that the amount of ash is quite high in the collected samples regardless of the gasification atmosphere. The presence of carbon together with the ashes indicates the presence of unconverted char in the two cyclones; see Fig. 6.
Figure 7. Percentage of organic matter and ash in the particulate matter collected in the two cyclones during the experiments as a function of the gasification temperature for the three distinct gasification atmospheres. (a) Organic matter, and (b) ash.

Finally, Fig. 8 shows soot and char formed during the experiments as a function of the gasification temperature for the three distinct gasification atmospheres. It is seen that the amount of soot increases as the temperature increases when the gasification takes place in the $\text{O}_2/\text{N}_2$ and $\text{O}_2/\text{CO}_2/\text{N}_2$ environments, while it remains almost constant in the $\text{O}_2/\text{H}_2\text{O}/\text{N}_2$ environment, Fig. 8a. This behaviour was also observed by Saha et al. [31] in the gasification of cow manure with pure CO$_2$ at temperatures from 800 to 1000 ºC, with an increase in the C present in the char particles from 2.3 to 6.3%. Previous studies on the formation of soot during the dry pyrolysis of acetylene, indicated an increase in its formation as the temperature increased [35, 36]. It seems that the presence of steam in the gasification atmosphere suppresses soot formation or increases soot oxidation, as has also been observed during pyrolysis of ethylene in the presence of increasing water vapour concentrations [37]. Consequently, gasification of the pig manure in the $\text{O}_2/\text{H}_2\text{O}/\text{N}_2$ atmosphere not only maximizes the H$_2$/CO ratio, as seen earlier, but also minimizes the presence of soot in the syngas.
Figure 8b indicates that the amount of char formed has a complex dependence on the gasification temperature and atmosphere. The gasification of the pig manure in the O$_2$/H$_2$O/N$_2$ atmosphere leads to higher amounts of char as the temperature increases, while the char evolution with the temperature is opposite for the other two gasification environments.

![Figure 8](image_url)

**Figure 8.** Soot and char formed during the experiments as a function of the gasification temperature for the three distinct gasification atmospheres. (a) Soot, and (b) char.

4. Conclusions

The present work examined the impact of the gasification temperature and atmosphere on the syngas composition (CO, H$_2$, CH$_4$ and CO$_2$) and formation of soot and char in the gasification of pig manure in a drop tube furnace. The temperature varied between 900 and 1200 ºC, and the gasification atmospheres included mixtures of O$_2$/N$_2$, O$_2$/CO$_2$/N$_2$ and O$_2$/H$_2$O/N$_2$. The main conclusions of this study are as follows.

1. The syngas H$_2$/CO ratio and its low heating value increase as the gasification temperature increases regardless of the gasification atmosphere, with the minimum
values of both parameters occurring when the gasification of the pig manure takes place in the O₂/N₂ environment.

2. The addition of H₂O to the O₂/N₂ gasification atmosphere augments significantly the syngas H₂/CO ratio, but does not enhance its low heating value; in contrast, the addition of CO₂ increases slightly the H₂/CO ratio, but significantly the heating value.

3. For the present configuration, the optimum operating conditions for the gasification of the pig manure in terms of syngas heating value and yield are a gasification temperature of 1200 ºC and a gasification atmosphere composed of a mixture of O₂/CO₂/N₂.

4. Soot yields increase as the temperature increases when the gasification takes place in the O₂/N₂ and O₂/CO₂/N₂ environments, but it remains almost constant in the O₂/H₂O/N₂ environment.

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