Wheat straw and pig manure gasification in a drop tube furnace

Tiago Miguel Martins Rio
tiago.m.rio@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal
November 2019

ABSTRACT

Due to greenhouse gas emissions and the consequent damage caused by global warming due to the use of fossil energy sources, the conversion of biomass to fuel has gained special attention. Biomass gasification can produce high quality syngas and solid by-products. The effect of the addition of steam and carbon dioxide in biomass gasification in a drop tube furnace (DTF) is reported in this project. Pig manure and wheat straw particles, ranging from 90 to 150 µm were the biomass used. The biomass feeding rate was fixed at 30 g/h and oxygen was fed to the reactor at a constant excess air ratio of 0.4. In wheat straw gasification, the influence of steam/biomass (S/B) ratio at 1000 ºC was examined while in pig manure gasification, the gasification atmosphere and temperature were the variables investigated. Pig manure gasification was performed in mixtures of nitrogen/oxygen, nitrogen/oxygen/steam and nitrogen/oxygen/carbon dioxide for distinct DTF wall temperatures between 900 and 1200 ºC. The results show that soot and char decrease, increasing the S/B ratio in wheat straw gasification. The syngas lower heating value, the carbon conversion efficiency and the cold gas efficiency were higher at S/B = 0.8, while at S/B = 1.7 the hydrogen/carbon monoxide ratio was higher. In pig manure gasification, the quantity of char particles was lower in the mixture nitrogen/oxygen/carbon dioxide for all temperatures investigated while for 1100 and 1200 ºC the quantity of soot particles was lower in the mixture of nitrogen/oxygen/steam. In this case, the syngas lower heating value and the cold gas efficiency were higher for the atmosphere with carbon dioxide while the carbon conversion efficiency and the hydrogen/carbon monoxide ratio were higher for an atmosphere with addition of steam.

Keywords

Wheat straw, pig manure, drop tube furnace, soot, char, syngas.

1. INTRODUCTION

Over the last few years, world energy consumption has been increasing. Currently, the main source of primary energy is the fossil fuel energy, but it is facing some problems. One of the problems is the climate change associated to the greenhouse gases emissions of fossil fuels, and another problem is the shortage of this energy source as the world energy demand increases. Therefore, to mitigate these problems it is necessary to explore renewable energy sources. Biomass is an abundant and available type of renewable energy source, being the fourth largest energy resource available, counting for 13% of the world´s energy consumption [1]. Pyrolysis, combustion and gasification are three examples of thermal conversion processes that differ mainly by their maturity level [2]. Biomass gasification seems to be the conversion process with more potential for energy production or biofuel synthesis, using the syngas produced [3].

Biomass is a biological material that is derived from living species which stores chemical energy in form of carbohydrates through photosynthesis process by combining solar energy and carbon dioxide [4]. It is considered a carbon neutral fuel, as there is an equilibrium between the release of CO_2 during the thermal conversion and the CO_2 absorbed by the biomass from the atmosphere through the photosynthesis in the growing stage [5].

Gasification is a thermochemical process that converts fossil or nonfossil fuels into useful convenient gaseous fuels or chemical feedstock. It takes place in a gasifier at high temperatures (700 – 1500ºC) in the presence of air, carbon dioxide, steam, oxygen under sub-stoichiometric conditions or a mixture of these. During biomass gasification, the biomass is converted into a syngas, however not all is converted. The rest of the products are char and soot particles and condensable products like tars [6, 7].

Gasification experiments have been carried out on different types of reactors, namely, moving bed, fluidized bed and entrained flow reactors. Due to the high operating temperatures, the use of small particles, the lower soot and tars formation and the high efficiency values achieved, the investigation on entrained flow reactors (EFR) has become important [8, 9]. In order to study the biomass conversion under EFR conditions on a laboratory scale, a drop tube furnace (DTF) was developed. A DTF is a relatively simple tool that allows to reproduce some characteristics on an EFR, such as the temperature, the heat flow, the residence time and the size of the biomass particles used [10, 11].

The main objective of this work is to quantify and characterize chemically and morphologically the resulting particulate matter (PM) and to analyse the quality and the gas composition of the producer gas for two different types of biomass. The main performance indicators for assessing the efficiency of the gasification process are the producer gas low heating value, LHV (MJ/Nm^3), the carbon conversion efficiency, CCE (%), the cold gas efficiency, CGE (%) and the hydrogen/carbon monoxide volume ratio, H_2/CO [2].

2. Material and methods

2.1. Fuel preparation and characterization

Pulverized wheat straw (WS) and pig manure (PMan) were the two types of biomass used to perform this study. Before starting the gasification tests, the WS and PMan were sieved between 90 and 150 µm and dried at 105 ºC for approximately 18 h to remove the excess moisture content. Table 1 shows the proximate analysis, the lower heating value and ultimate analysis for each biomass.

Table 1 - Properties of WS and PMan.

Parameter	WS	PMan
Proximate analysis (wt.%, as received)		
Moisture	8.0	17.8
Volatile matter	64.9	42.7
Ash	14.7	33.7
Fixed carbon (by dif.)	12.4	5.8
Heating value (MJ/kg, as received)		
Low	13.0	9.4
Ultimate analysis (wt.%, dry ash free)		
C	41.1	49.7
H	5.3	5.4
N	0.7	5.4
S	< 0.02	1.6
O (by dif.)	52.6	37.9

2.2. Experimental setup and conditions

Figure 1 illustrates the experimental setup schematic. The gasification system consists of a biomass feeder, a gas supply system, a vertical drop tube reactor, a particulate collection system and a gas sampling and analysis system. The place where the gasification takes place consists of a nonporous mullite tube with a total length of 1750 mm and an inner diameter of 40 mm. Along the furnace, there are three equally spaced thermocouples (type k) to monitor continuously the wall temperatures. This furnace can reach a maximum temperature of 1300 ºC.

The feed system consists of a twin-screw volumetric feed where the biomass is poured. The injector is water cooled and it is inserted into the vertical tube. It has a central pipe for the inlet of the biomass particles and the carrier gas (N_2) and a concentric passage for the introduction of a secondary stream. The secondary stream is a mixture of nitrogen, oxygen and steam or carbon dioxide. The steam is produced on a generator controlled by dedicated software and the remaining gases are supplied from bottles and the flow rates are controlled by manual flow meters. The particle collection system is located at the bottom of the reactor. It is composed by an in-house made cyclone for particles larger than 10 µm, a *Dekati*® cyclone that provides a cut size of 10 µm, and a *Dekati*® low pressure impactor (thirteen stages) to collect the finer particles between 10 µm and 30 nm. To avoid gases condensation, the *Dekati* cyclone and the DLPI were kept at 150 ºC by two Winkler heating blankets. Through SEM, EDS and burnout analysis the PM was separated into soot and char particles.

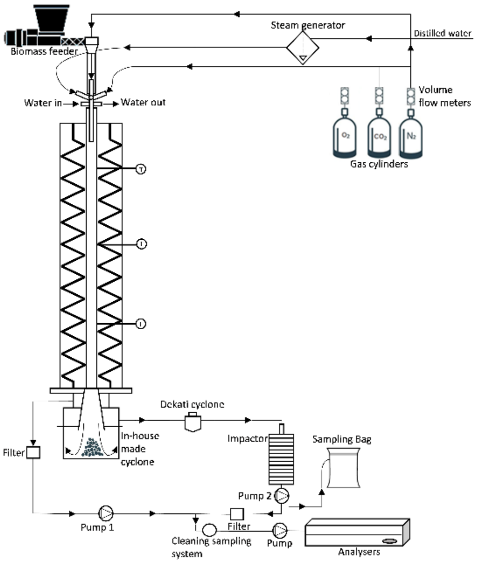


Figure 1 - Schematic of the experimental setup.

The experimental part was divided into two parts. On the first part, the influence of steam/biomass (S/B) ratio was studied using WS as the biomass. On the second part, the influence of three different gasifying atmospheres at four different temperatures on PMan gasification were investigated. The excess air coefficient (λ) used in both parts was 0.4 and the biomass particle residence time in the reactor was approximately 2 - 3 seconds. The experimental schedules are presented in the Tables 2 and 3.

Table 2 - Experimental schedule for the study of the effect of S/B ratio in WS gasification.

No.	T_r (°C)	$\dot{m}_f$ (g/h)	$\dot{m}_{steam}$ (g/h)	S/B (g/g)	$\dot{V}_{steam}$ (L/min)	$\dot{V}_{O_2}$ (L/min)	$\dot{V}_{N_2}$ (L/min)	Total (L/min)
1	1000	30	0	0	0	0.11	9.89	10
2			15	0.5	0.54		9.35	
3			25	0.8	0.90		8.99	
4			50	1.7	1.80		8.09	

Table 3 - Experimental schedule for the study of three gasification atmospheres at four different temperatures for PMan gasification.

No.	T_r (°C)	$\dot{m}_f$ (g/h)	$\dot{V}_{N_2}$ (L/min)	$\dot{V}_{O_2}$ (L/min)	$\dot{V}_{CO_2}$ (L/min)	$\dot{V}_{steam}$ (L/min)
1	900	30	10	0.11	---	---
2	1000				---	---
3	1100				---	---
4	1200				---	---
5	900	30	10	0.11	0.54	---
6	1000					---
7	1100					---
8	1200					---
9	900	30	10	0.11	---	0.54
10	1000				---	
11	1100				---	
12	1200				---	

The experimental procedure for both parts is summarized next. After turning on the gas analysers and cooled water for the injector and the electrical furnace to a desired temperature, the biomass feedstock with the required size is loaded for the biomass feeder system. Then, the nitrogen with the appropriate flow rate is turned on to remove all the air present in the reactor. After this, the required amount of oxygen is added, and steam or carbon dioxide are also added to complete the necessary gasification atmosphere. After the conditions are stable, the biomass feeder system is turned on. During the first five minutes, the resulting gas flows directly to the gas analysers to stabilize the reactions inside the furnace. For the next fifteen minutes, the resulting gas flows the other path, passing the cyclone and the impactor, where the char and soot particles are collected. After this time, the test is finished, the cyclones and the impactor are taken out and their content is weighed and properly stored for subsequent analysis.

3. Results and Discussion

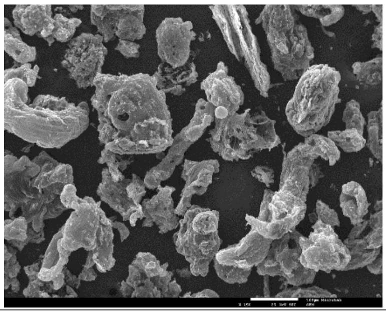
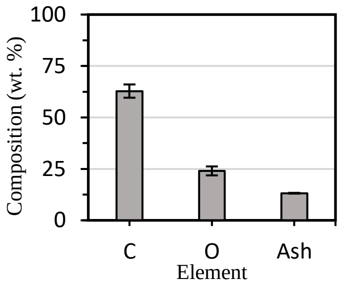
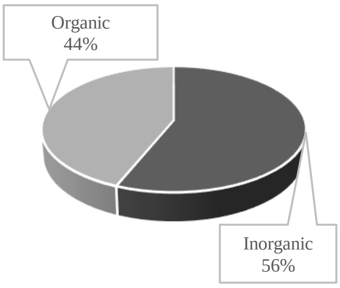
The results and discussion are presented into two parts. The effect of S/B ratio on WS gasification is presented in the first part. The influence of the gasification atmospheres at four different temperatures on PMan gasification is presented next.

3.1. Effect of S/B ratio on WS gasification

3.1.1. Formation and classification of PM

The PM resulting from biomass gasification are essentially char, soot and ash particles. To distinguish the different types of particles, SEM and EDS analysis were performed for the PM collected in the cyclone and impactor. To consolidate the EDS results, a burnout experiment was performed only for the PM collected in the cyclone. Table 4 shows an example of SEM image, EDS and burnout analysis for the particles collected in the cyclone at S/B = 0.8.

Table 4 - SEM, EDS and burnout analysis for WS gasification for PMs collected in cyclone at S/B = 0.8.

SEM Image	EDS Analysis	Burnout Experiment
	 	

For the four conditions analysed, the particles collected in the cyclones are very similar, have irregular shapes and pores. From the EDS analysis, these particles are constituted of about 60 wt.% of carbon, 23 to 27 wt.% of oxygen and 13 to 20 wt.% of ash, regardless the S/B ratio used. Through the burnout experiment, it was observed an organic content between 40 to 48 wt.%. From the morphological characteristics and chemical composition, it is possible to state that the PM collected in cyclone are essentially char.

Table 5 presents the SEM and EDS analysis for the PM collected in stages 3 and 12 of the thirteen-stage cascade impactor at S/B = 0.8. For stage 3, the SEM image shows uniform particles that form agglomerates of about 200 nm, while, from the EDS analysis, the particles have 80 to 90 wt.% of carbon. On other hand, for stage 12, the particles have an irregular shape, porosity and they are constituted of about 54 to 63 wt.% of carbon. Observing the SEM images and EDS analysis for the PM collected in cyclone and all the stages of the impactor for the four conditions studied, it can be concluded that the PM collected in cyclone and stages 9 to 13 are essentially char particles, while the particles collected in stages 1 to 8 of impactor are soot particles.

Table 5 - SEM image and EDS analysis for WS gasification for PMs collected in stages 3 and 12 of the impactor at S/B = 0.8.

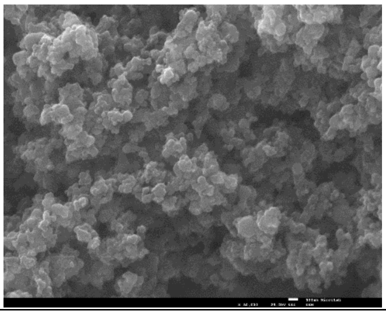
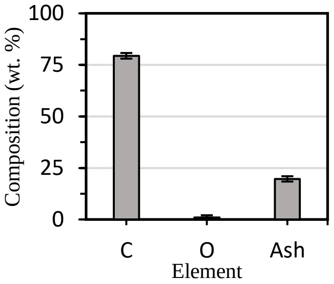
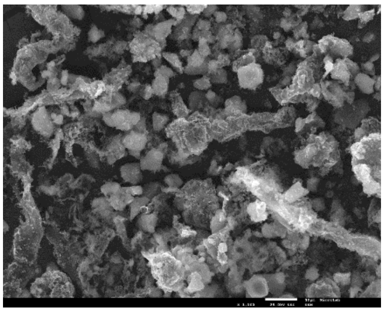
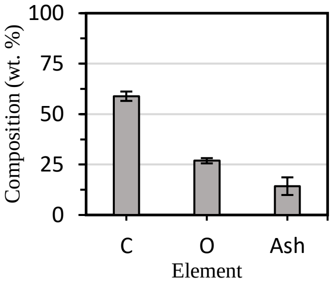
Stage	SEM Image	EDS Analysis
3		
12		

Figure 2 illustrates the effect of S/B ratio on formation of soot and char particles and on char, soot and volatiles yields. From the Figure 2, it can be observed that both char and soot decrease as steam is added to the gasifying atmosphere. The quantity of char particles decreased from 145.55 to 127.51 mg/g dry biomass while the soot particles decreased from 5.35 to 2.40 mg/g dry biomass, when the S/B ratio increased from 0 to 1.7. In the case of volatiles yield, as steam was added, it increased from 84.9 to 87.01 wt.% while char and soot yields decreased. The water/gas reaction may be the justification for this behaviour, since in this reaction, the carbon reacts with steam, originating CO and H_2.

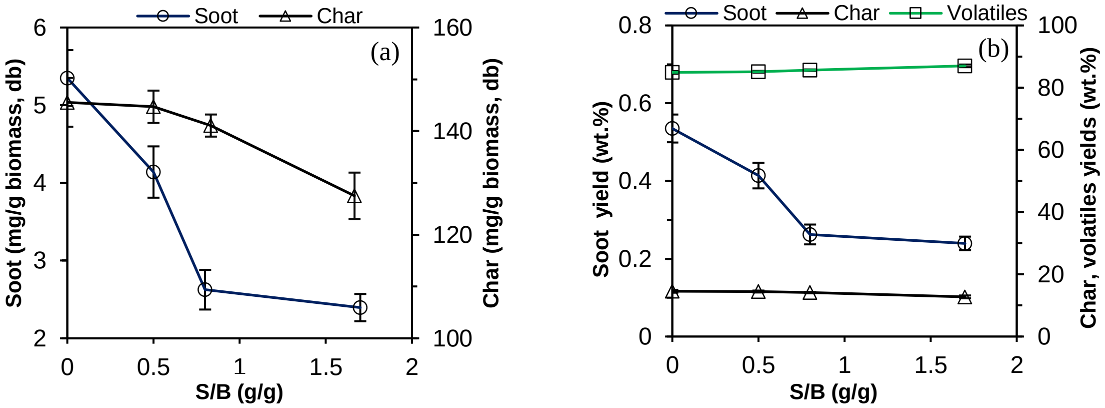


Figure 2 – Effect of the S/B ratio on the formation of soot and char particles (a), and on the char, soot and volatiles yields (b).

3.1.2. Composition and quality of the producer gas

On these experiments, the producer gas was mainly formed by N_2 (~ 97 vol.%), as a result of the large amount of nitrogen used. Figure 3 (a) illustrates the gas composition of the syngas as a function of the S/B ratio. Increasing the S/B ratio from 0 to 1.7, the H_2 yield increased significantly from 10.25 to 17.28 vol.%, while the CO_2 yield slightly decreased from 35.14 to 29.57 vol.%, and the CH_4 yield remained almost constant close to 7 vol.%. The CO yield increased slightly initially but then decreased from 52.92 to 46.10 vol.% when increasing the S/B from 0.5 to 1.7. Hernández et al. [12], in air-steam gasification, obtained similar behaviours for the volume concentrations of each syngas specie, varying the S/B ratio from 0.64 to 1.57. Due to the increase of steam involved in the reactions, the improvement of the steam reforming of char and methane, and the water/gas shift reaction occur, and this can explain the trends shown on the plot.

The syngas LHV (Figure 3 (b)) increased from 9.29 to 10.54 MJ/Nm^3, when the S/B ratio increased from 0 to 0.8. For S/B = 0.8, the LHV decreased to 10.07 MJ/Nm^3, as the result of the decrease of CO and CH_4, despite the increase in H_2 yield. The CGE and CCE (Figure 3 (c)) presented similar trends. The CGE increased from 39.81 to 47.06% and CCE remained close to 80% when increasing the S/B ratio from 0 to 0.8. For S/B = 0.8, the CGE and CCE decreased to 40.70 and 66.81%, respectively. These behaviours can be explained by the decrease in the syngas LHV and the decrease in the carbon leaving the reactor through the syngas, respectively. The H_2/CO ratio was enhanced by the increase of S/B ratio, because of the high increase in H_2 yield and the small CO yield variation.

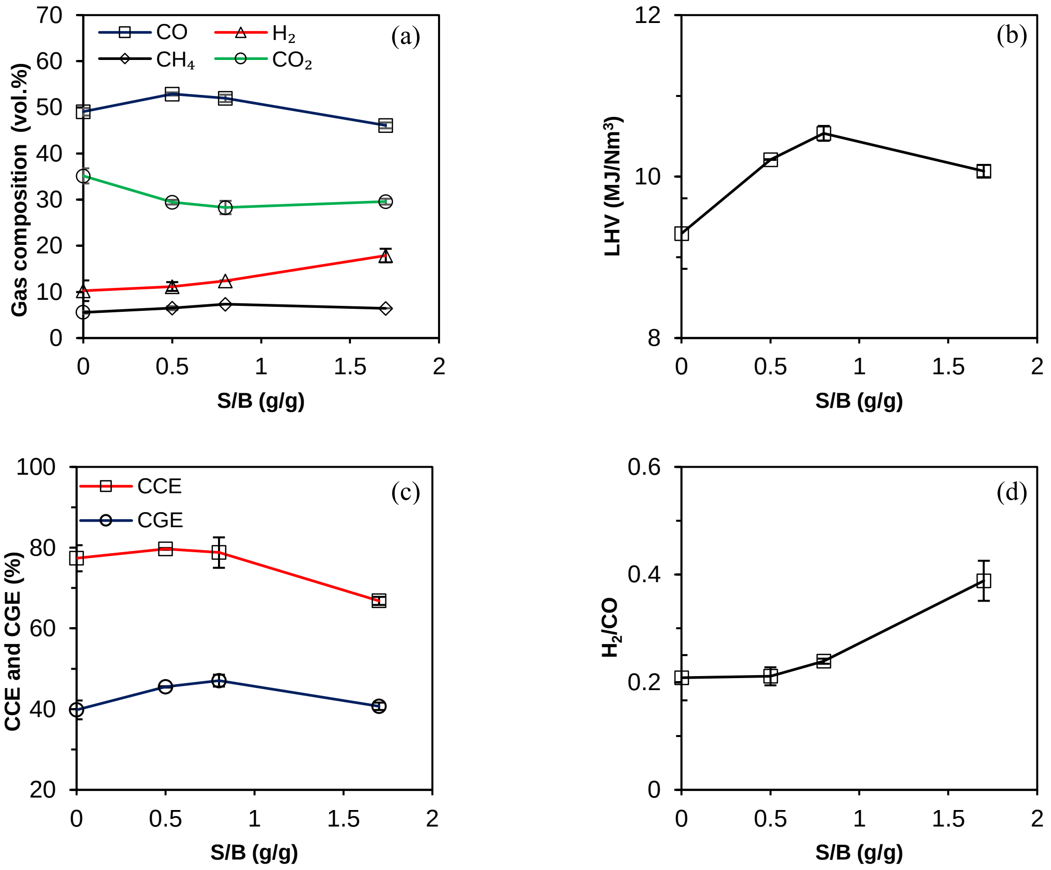


Figure 3 – Effect of S/B ratio on syngas composition (a), and on gasification performance parameters: LHV (b), CCE and CGE (c) and H_2/CO (c).

3.2. Effect of gasification atmosphere and temperature on PMan gasification

3.2.1.Formation and classification of PM

To characterize the PM resulting from PMan gasification, a SEM, EDS and a burnout analysis were also performed to distinguish between char and soot particles. The SEM images for the PM collected in cyclone and impactor are very similar to those obtained for WS gasification, however by EDS analysis, different results were obtained. A relatively low percentage of carbon, between 4 and 30 wt.%, and a high percentage of ash, between 39 and 47 wt.% were obtained for the particles collected in cyclone, regardless the temperature and gasification atmosphere examined. For the particles collected in impactor, the EDS analysis showed a low carbon content, around 18 wt.% for stages 9 to 13 and for stages 1 to 8, the EDS analysis presented a relatively higher content, about 55 wt.%. Thus, char and soot particles were separated in the same way as in WS gasification.

Figure 4 shows the quantity of char and soot collected on PMan gasification at different gasification atmospheres as a function of the temperature. From Figure 4, the amount of char, collected mostly in cyclone, depends greatly on the gasification atmosphere. The $N_2/O_2/CO_2$ atmosphere generated the minimal quantity of char particles at all temperatures studied, compared to the other atmospheres. In this atmosphere, the amount of char particles decreased from 418.77 to 249.56 mg/g biomass. At highest temperatures, 1100 and 1200 ºC, the $N_2/O_2/H_2O$ atmosphere originated less soot particles and the N_2/O_2 atmosphere originated more. Although the amount of soot is very small, it can be stated that adding steam or CO_2 to the atmosphere, above 1000 ºC, the formation of soot particles is reduced.

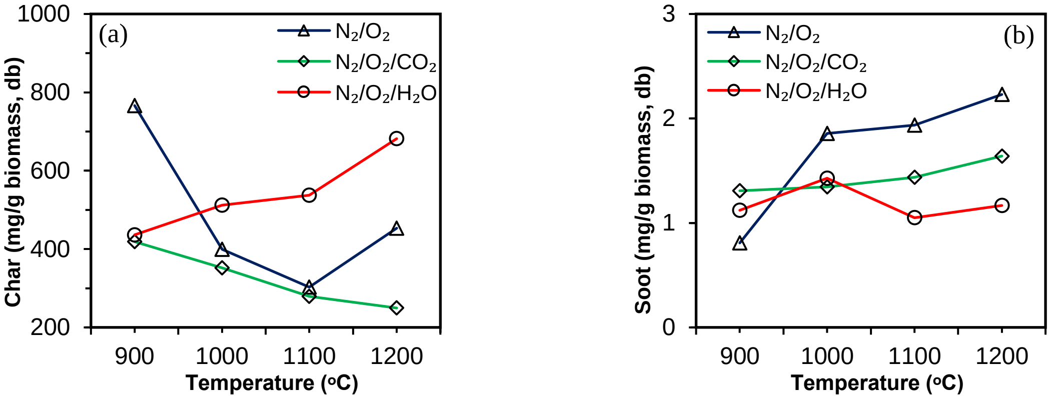


Figure 4 - Amount of char (a) and soot (b) obtained on PMan gasification at different gasification atmospheres and temperatures.

3.2.2. Composition and quality of the producer gas

As in the case of WS gasification, the producer gas was also mainly formed by N_2 (~ 97%). Figure 5 illustrates the behaviour of gas species for each gasification atmosphere as a function of the operating temperature. For the temperature range examined, it was found that the CO_2 yield decreased while the H_2 yield significantly increased, between 900 and 1200 ºC, for all the gasification atmospheres. However, the CO yield slightly decreased for N_2/O_2 and $N_2/O_2/H_2O$ atmospheres and increased for the $N_2/O_2/CO_2$ atmosphere as the temperature increased from 900 to 1200 ºC. The CH_4 yield had a small variation, but it was higher for the $N_2/O_2/CO_2$ atmosphere. At 1200 ºC, this atmosphere presented the highest CO yield and the smallest CO_2 yield with 55.89 and 8.98 vol.% respectively. The H_2 production was higher at 1200 ºC for the $N_2/O_2/H_2O$ atmosphere followed by $N_2/O_2/CO_2$ atmosphere and finally the N_2/O_2 atmosphere with 29.83, 25.74 and 15.09 vol.%, respectively. Hussein et al. [13] studied the gasification of chicken manure in three gasifying atmospheres and found similar behaviours for the gas species when increasing the temperature. The increase in temperature benefits the endothermic reactions, as the water/gas reaction, the methane steam reforming and Boudouard reaction. The first two reactions produce CO and H_2 consuming H_2O and CH_4 and the later consumes CO_2 producing CO. These endothermic reactions may explain the decrease in the CO_2 yield and the increase in H_2 yield. The water/gas shift reaction can explain the small variation of CO yield, on N_2/O_2 and $N_2/O_2/H_2O$ atmospheres, because it is slightly exothermic and occurs easily. In this reaction the H_2 and CO_2 are produced, and CO and H_2O are consumed. The addition of steam should promote the water/gas reaction and the methane steam reforming reaction, but the water/gas shift reaction also occurs. This explains the low CO yield variation and the larger H_2 yield when compared to the other gasification atmospheres (N_2/O_2 and $N_2/O_2/CO_2$).

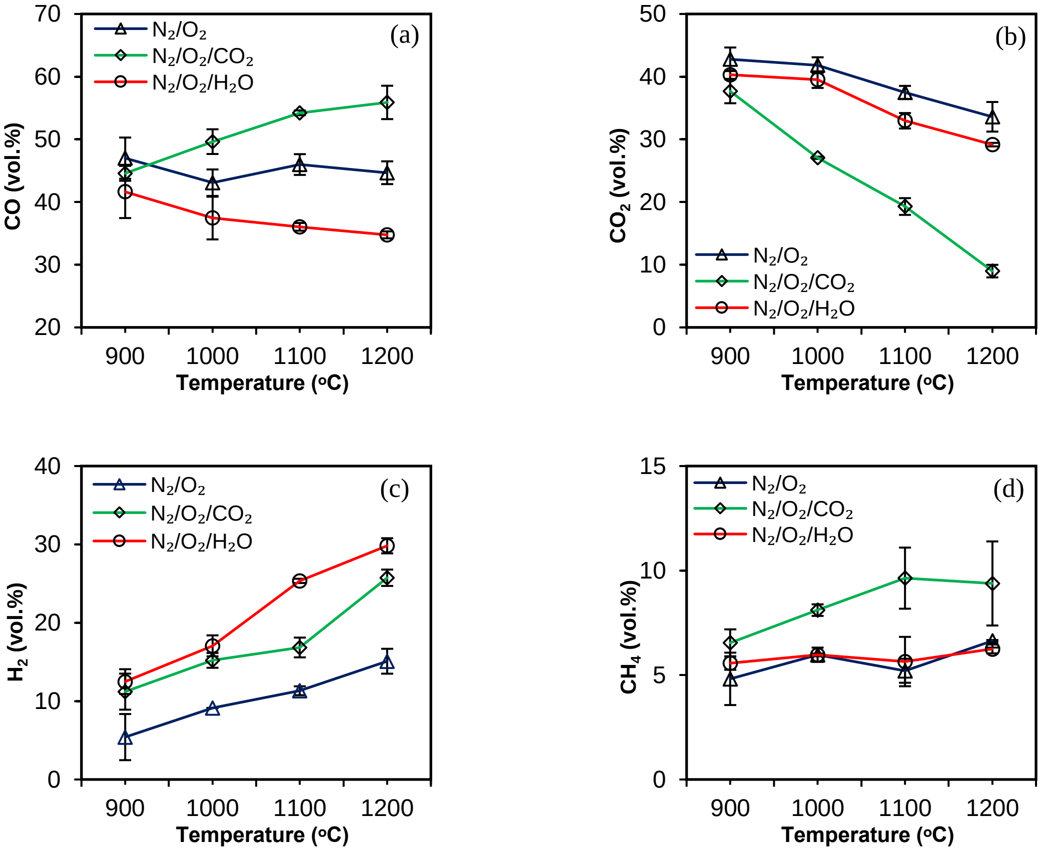


Figure 5 - Effect of temperature and gasification atmosphere on CO, CO_2, H_2 and CH_4 yield for PMan gasification.

Figure 6 illustrates the influence of temperature and gasification atmosphere on the performance parameters: LHV, CGE, CCE and H_2/CO. The syngas LHV (Figure 6(a)), increased for an operating temperature between 900 and 1200 ºC for the three gasification atmospheres, but it is more pronounced in the atmosphere with CO_2. In this atmosphere, the LHV increased from 9.19 to 13.20 MJ/Nm^3. This result can be attributed to the fact that CO yield and CH_4 yield are more pronounced in this atmosphere than in the others. In N_2/O_2 and $N_2/O_2/H_2O$ atmospheres the LHV slightly increased from about 8.60 to 9.85 MJ/Nm^3.

As the temperature increased from 900 to 1200 ºC, CGE (Figure 6(b)) also increased for all gasification atmospheres examined. At 900 ºC, the CGE was about 40%, similar for the three gasification atmospheres while for higher temperatures the values were different. At 1200 ºC, the CGE was higher for the atmosphere with CO_2, followed by the atmosphere with steam and finally for the N_2/O_2 atmosphere with 87.71, 77.84 and 58.37%, respectively. This tendency could be explained by the increase of the LHV for the $N_2/O_2/CO_2$ atmosphere and by the increase in the syngas yield for the $N_2/O_2/H_2O$ that is higher than in N_2/O_2 atmosphere.

In general, the CCE (Figure 6(c)) increased with temperature for all the gasification atmospheres. At 1200 ºC, the CCE was higher for the $N_2/O_2/H_2O$ atmosphere with 94.92% because the syngas yield was more pronounced in this atmosphere. At 900 ºC, the CCE was identical for the N_2/O_2 and $N_2/O_2/H_2O$, about 75% and slightly lower for the $N_2/O_2/CO_2$ atmosphere, about 69.65%.

Due to the high increase in H_2 yield and a small variation of CO yield for the three gasification atmospheres, the H_2/CO ratio (Figure 6(d)) was enhanced, increasing the temperature from 900 to 1200 ºC. At 1200 ºC, for instance, the H_2/CO ratio was maximum for the $N_2/O_2/H_2O$ atmosphere, reaching 0.86.

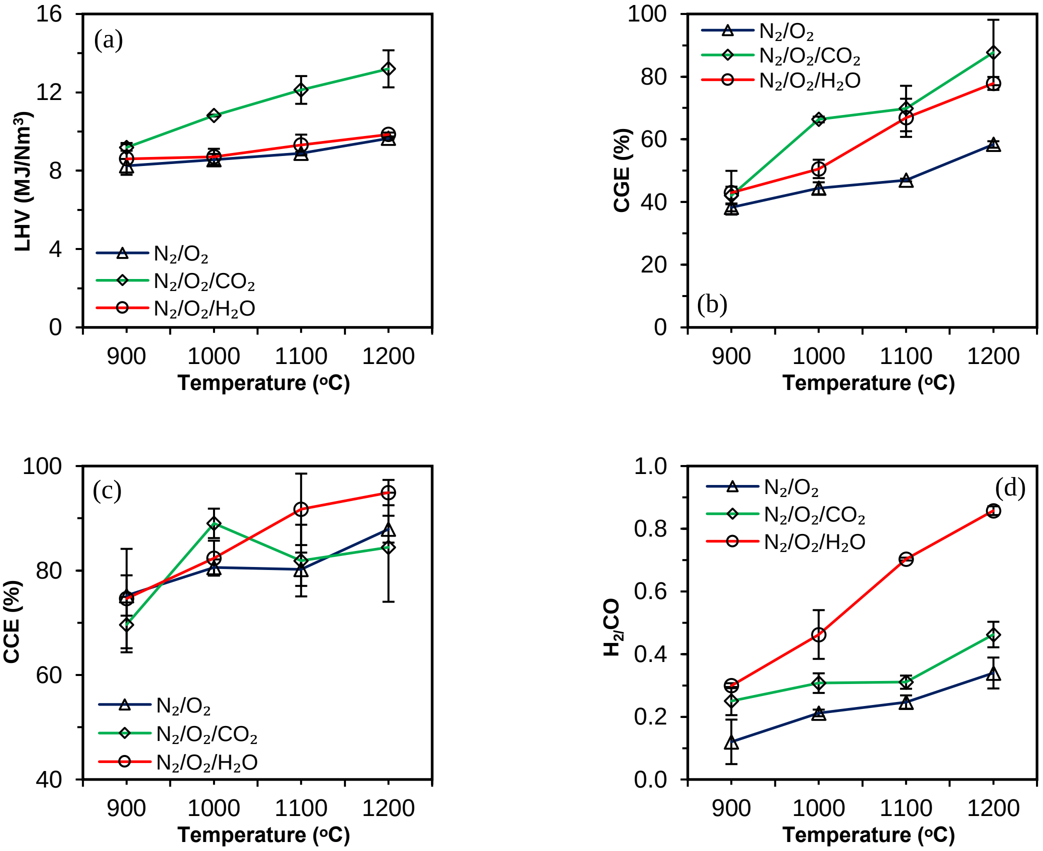


Figure 6 – Effect of temperature and gasification atmosphere on the gasification performance indicators: LHV (a), CGE (b), CCE (c) and H_2/CO (d).

4. Closure

4.1. Conclusions

In the present work, two types of biomass were used. The effect of S/B ratio was studied in wheat straw gasification while the influence of temperature and gasification atmosphere were analysed in the gasification of pig manure.

In wheat straw gasification, varying the S/B ratio at a constant temperature, it can be concluded that with higher S/B ratio (up to the maximum analysed), less char and soot are formed. Thus, increasing the steam content in the gasification atmosphere reduces the number of solid particles formed and increases the quantity of volatiles formed. The percentage of carbon present in the originated char particles also reduces with the increase of the S/B ratio, i.e., the conversion of carbon present in the biomass is increased with the increase of steam in the gasification atmosphere. Since soot is an undesirable product, WS gasification at S/B = 1.7 can be a good solution to decrease its production. Results for the syngas composition and quality indicate that higher S/B ratios result in higher H_2 yield and higher H_2/CO while the LHV, CCE and CGE present a maximum value at S/B = 0.8.

In the case of pig manure gasification, it is concluded that the number of solid particles formed depends significantly on the gasification atmosphere used. If the objective of gasification is to generate the smallest amount of char particles, it can be concluded that the atmosphere with CO_2 at 1200 ºC is the best. In order to reduce the quantity of soot formed (an undesirable product), an atmosphere with steam at high temperatures should be used, although the amount of soot is always reduced in all cases. However, further tests are required for each condition to verify this trend. The syngas composition obtained in the gasification of pig manure showed that the CO and CH_4 yields are higher for a gasification atmosphere with CO_2, while the CO_2 and H_2 yields are higher for an N_2/O_2 atmosphere and for an atmosphere with steam, respectively. The LHV and the CGE were higher for the atmosphere with CO_2 addition, while the CCE and the H_2/CO were higher for the atmosphere with steam addition, at 1200 ºC.

4.2. Future work

In this master thesis, the impact of various operating conditions on biomass gasification in a drop tube reactor was studied and discussed. The variation of the S/B ratio at a constant temperature, the influence of steam or carbon dioxide addition to a gasification atmosphere at different temperatures and the use of two types of biomass from different sources were the variants studied throughout this work.

For future work, it would be interesting to study the influence of other operating parameters, such as, the biomass particle size, the residence time or the impregnation of biomass with inorganics. These parameters may affect the amount and size of the resulting solid particles as well their composition and the syngas composition and quality. Another product obtained in the gasification process is tar, a black and viscous fluid, undesirable for downstream applications. It would be interesting to study its formation and composition in different gasification atmospheres with different types of biomass. The gas produced during the gasification process is also important to examine as there are several downstream applications. To improve the quality of the gas obtained, further investigation about syngas cleaning technologies would also be interesting.

5. References

[1] WBA global bioenergy statistics, World Bioenergy Association, 2018.

[2] M. La Villetta, M. Costa, and N. Massarotti, Modelling approaches to biomass gasification: A review with emphasis on the stoichiometric method, Renew. Sustain. Energy Rev., vol. 74, no. February, pp. 71–88, 2017.

[3] V. S. Sikarwar, M. Zhao, P. S. Fennell, N. Shah, and E. J. Anthony, Progress in biofuel production from gasification, Prog. Energy Combust. Sci., vol. 61, pp. 189–248, 2017.

[4] S. K. Sansaniwal, K. Pal, M. A. Rosen, and S. K. Tyagi, Recent advances in the development of biomass gasification technology: A comprehensive review, Renew. Sustain. Energy Rev., vol. 72, no. December 2015, pp. 363–384, 2017.

[5] P.Basu, Biomass gasification and pyrolysis: Practical design and theory, 1st ed., Elsevier Inc., 2010.

[6] S. De, A. K. Agarwal, V. S. Moholkar, B. Thallada, Coal and Biomass Gasification, 2018.

[7] E. R. Widjaya, G. Chen, L. Bowtell, and C. Hills, Gasification of non-woody biomass: A literature review, Renew. Sustain. Energy Rev., vol. 89, no. September 2016, pp. 184–193, 2018.

[8] K. Qin, W. Lin, P. A. Jensen, and A. D. Jensen, High-temperature entrained flow gasification of biomass, Fuel, vol. 93, pp. 589–600, 2012.

[9] J. Zhou, Q. Chen, H. Zhao, X. Cao, Q. Mei, Z. Luo, K. Cen, Biomass-oxygen gasification in a high-temperature entrained-flow gasifier, Biotechnol. Adv., vol. 27, no. 5, pp. 606–611, 2009.

[10] S. Septien, S. Valin, M. Peyrot, B. Spindler, and S. Salvador, Influence of steam on gasification of millimetric wood particles in a drop tube reactor : Experiments and modelling, Fuel, vol. 103, pp. 1080–1089, 2013.

[11] Y. Zhang, S. Kajitani, M. Ashizawa, and Y. Oki, Tar destruction and coke formation during rapid pyrolysis and gasification of biomass in a drop-tube furnace, Fuel, vol. 89, no. 2, pp. 302–309, 2010.

[12] J. J. Hernández, G. Aranda, J. Barba, and J. M. Mendoza, Effect of steam content in the air-steam flow on biomass entrained flow gasification, Fuel Process. Technol., vol. 99, pp. 43–55, 2012.

[13] M. S. Hussein, K. G. Burra, R. S. Amano, and A. K. Gupta, Temperature and gasifying media effects on chicken manure pyrolysis and gasification, Fuel, vol. 202, pp. 36–45, 2017.