

Fixed bed gasification of wood char: Characterisation of a new continuous downdraft reactor

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Abstract

A staged gasification process coupled with a gas engine is one of the most promising technologies for small and medium sized electricity production.

The purpose of this work was to design and build new experimental equipment to characterise the wood char gasification stage in fixed bed/staged reactors. The Continuous Fixed Bed reactor (CFiB) at CIRAD replicates the gasification zone separately from the rest of the process. Instrumentation is a key point of the equipment. Sampling and measuring probes are positioned all along the char bed, every 10 cm, enabling online analysis of temperature, pressure and gas composition, along with condensate tracking.

Accurate heat and mass balances were carried out to validate reactor performance and the methodology. Lastly, to illustrate the high potential of this research, equipment profiles for temperatures and gas concentrations along the bed are presented and discussed.

1. Introduction

Gasification has recently received increasing attention with the first successful plants for electricity production from biomass [1]. Today, the new challenge is to extend its use to other markets such as biofuels or green electricity, by coupling gasifiers with technologies such as Fischer-Tropsch or fuel cells. A viable development of these processes is conditioned by the improvement of both overall efficiency and the quality of the gas produced, and by the emergence of solutions to the remaining technological brakes. Achievement of these objectives still requires improvement of scientific knowledge in chemical reactions and phenomena involved in the gasification process.

Staged gasification, as demonstrated by the Viking plant [2] and more recently Xylowatt technology, confirms its solution for small and medium sized energy production. In staged gasifiers, pyrolysis and gasification reactions occur in different reactors. The main advantage is to enable independent control of the main two steps of the process.

Many questions remain and in particular regarding the thermochemical behaviour of the continuous fixed char bed. This zone of the process is fundamental as it produces the main part of the syngas ($\text{CO} + \text{H}_2$) through low and limiting reactions in terms of conversion times.

Most of the studies on fixed bed gasifiers have focused on the overall behaviour of the process [2-9] and have not paid specific attention to the heterogeneous gasification zone.

Few authors have focused on characterising the char bed gasification zone. Bhattachaya [10] measured the temperatures every 10 cm in a fixed bed of coal char but under batch operating conditions. The most relevant study is reported by Gobel et al., [11] in their work on the Viking staged reactor.

Our work set out to study such staged processes and in particular to focus on wood char gasification, since this reaction is known to be limiting in terms of kinetics. Moreover, this reactive zone, where carbon is converted by steam and CO_2 into CO and H_2 , has a major impact on both process efficiency and gas quality. For this purpose, we designed, constructed and tested an original Continuous Fixed Bed reactor (CFiB) equipped with precise and abundant instrumentation, in order to capture the main phenomena occurring in the reduction zone during the char bed gasification process. Understanding the coupling between chemical reaction kinetics, heat/mass transfers and mechanical behaviour of the char bed during its gasification is the objective of this ongoing work.

2. Materials and methods

The CFiB reactor

The Continuous Fixed Bed Reactor (CFiBR) was designed and built at CIRAD (fig 1). It consists of a refractory stainless steel tube (4) 20 cm in diameter and 160 cm long, surrounded by refractory wool insulation (5).

The atmosphere of the reactor, i.e. temperature and reactant gases (H_2O and CO_2) is generated by the exhausts of two propane burners (3) of 15 kW each. The flow rates of propane and air are accurately controlled by two Brooks mass flow meters/controllers. The propane/air ratio can also be varied to obtain the required excess air and thus the residual oxygen in gases. Additional heated steam can be added below the combustion chamber by way of a specially designed steam generator/preheater.

A conveyer (1) is used to feed char from the top of the reactor at a flow-rate between 0 and 3 kg/h. A given mass of char is uniformly distributed on the belt whose low speed controls the char flow-rate. A system of two pneumatic valves (2) prevents air from entering the reactor during char introduction through alternative automated opening and closing cycles.

Inside the reactor, the char settles in a bed that can reach 80 cm thick. The bottom of the reactor is equipped with a plate with holes 1 cm in diameter and a scraper (6), which is activated manually and enables ash removal from the reactor during experiments. The plate is generally positioned 5 cm inside the reactor to reduce thermal losses at the outlet. This plate can be moved down vertically to extract particles larger than 1 cm by the periphery, especially at the end of the experiments.

Instrumentation is a key point of the equipment.

Sampling and measuring probes are positioned all along the char bed, every 10 cm, enabling online analysis of the temperature, pressure, and gas composition, along with condensate tracking.

The reference char (production and characterisation)

The initial samples consisted of maritime pine wood chips delivered from Ardeche (France). The proximate and ultimate analyses of the wood, measured in compliance with standards, are presented in table 1. The volatile matter percentage was as high as 82.6%, and the ash content of the wood was low: 1.6%.

Char was produced in a screw pyrolysis reactor. The reactor was actually the pyrolysis unit of the CIRAD 2-stage gasifier, which was disconnected from the rest of the gasifier. Pyrolysis operating conditions are known to influence significantly the nature of the char produced. Consequently, use of this pyrolysis reactor was guaranteed to give a char representative of those entering an industrial gasifier. The pyrolysis unit has been amply described elsewhere [12]. Roughly, it consists of a steel cylinder provided with a heating system. The cylinder is horizontal and crossed by an endless screw which leads the raw material from its entrance to its exit. For char production, the operating conditions were: 750°C, 1h, 20 kg/h.

The proximate and ultimate analyses of the char produced are presented in table 1. Note that the volatile matter content was low enough (lower than 5%) not to disrupt our study focusing on char bed behaviour. About 200 kg of char were produced to carry out all the set-up and characterisation tests.

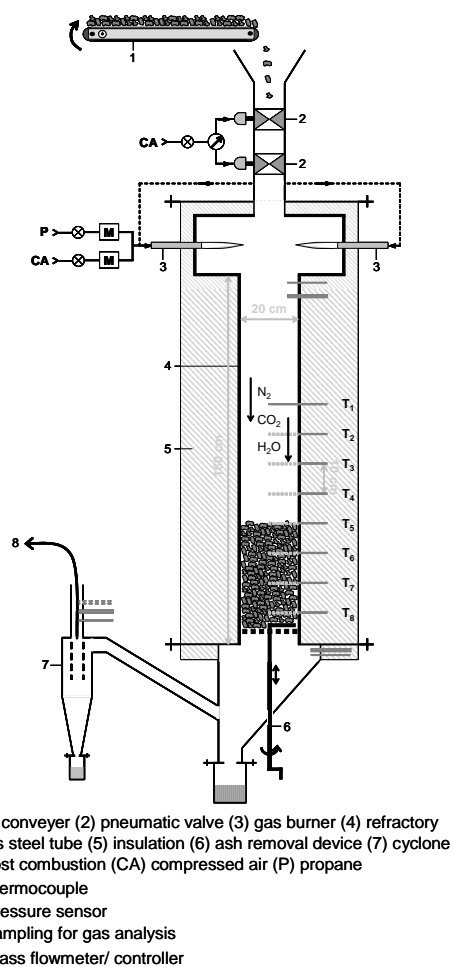


Figure 1: The CFiB Reactor

Properties Material	Proximate analysis (% w)				Ultimate analysis (% w)				
	Moisture content	Volatile matter	Ash content	Fixed carbon	C	H	O	N	S
Woodchips	12	82.6	0.2	17.2	45	5.7	42.8	<0.3	<0.1
Char	1.6	4.9	1.3	93.5	92.0	1.4	5.1	<0.3	<0.1

Table 1: Proximate and ultimate analysis of the woodchips from maritime pine

Instrumentation and analysis

Reactor control and understanding require precise instrumentation. Special instrumentation has been installed for access to the temperature, pressure, gas composition and residual solid properties. Temperature and gas concentration in the bed were continuously measured through special probes every 10 cm along the char bed. The probes located at the centre of the reactor were spirally positioned to avoid disturbing char flow in the same plane of the reactor. Each probe consisted of a 1 mm type K thermocouple inserted in a 4 cm refractory stainless steel sampling pipe. The thermocouple extended 5 mm beyond the sampling pipe. These probes enabled measurement of temperature and gas concentration axial profiles. Moreover, each probe could also be manually displaced along the diameter to measure radial profiles at a given height in the char bed. The sampling probes could also be used for pressure measurements along the bed. Temperatures were measured instantaneously at different heights but gas sampling and analysis had to be carried out successively at each location. Gases passed through a sampling line described in figure 2. The gases were first cooled in the 4 impingers filled with isopropanol where condensates were removed from the gases. Dry gases successively encountered a filter, a silicagel water trap, a volumetric counter. Part of the gases went to a micro GC analyser with 2 columns enabling quantification of molar concentrations of CO, N₂, O₂, H₂, CO₂, CH₄, C₂H₄, and C₂H₆. Water and organic compounds collected in condensates were measured later on in the lab. The Karl Fisher technique was used to quantify water content and GC/MS to identify and quantify organic compounds.

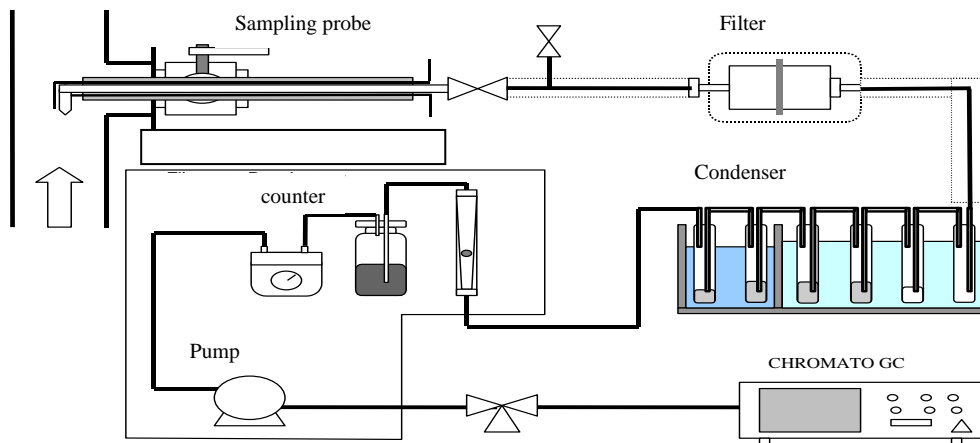


Figure 2: The sampling line

The ashes containing residual carbon were sampled every 10 minutes at the bottom of the reactor when the ash removal system was operated. The ashes collected were continuously weighed to control the bed height accurately.

The collected ashes were weighed to calculate char conversion directly. Char conversion was also calculated using the ash tracer method which sets out to compare ash content in the initial char and in the residue. The following correlation gives the conversion rate:

$$X = \frac{1 - C_{ash}^{char} / C_{ash}^{res}}{1 - C_{ash}^{char}}$$

Where C_{ash}^{char} and C_{ash}^{res} are respectively the ash content in the initial char and in the carbon residue collected.

3. Results and discussion

For the tests, the power of the propane burners was set to 11 kW, with 20% excess air; the charcoal flow rate was fixed at 28 g/min (1.68 kg/h). The theoretical composition of the exhausts, i.e. the atmosphere of the reactor, is presented in Table 2. The temperature of the gases entering the bed was 1020°C.

H ₂ O	CO ₂	O ₂	N ₂
30%	8%	2,7%	59,3%

Table 2: Composition of the wet exhaust gas

After starting the experiment, 6 hours were necessary to reach the steady state. It was attested by the simultaneous stability versus time of:

- i. the bed level
- ii. the temperatures inside the reactor
- iii. the flow rate and composition of the gas produced
- iv. the flow rate and composition of the ash removed

Figure 3 confirms the stability of the bed level and of the temperatures. Temperature T₄ fluctuated because the corresponding thermocouple, positioned at the surface of the bed level, was alternately inside and outside the bed. Moreover it played a major role as it was our indicator of the constant level of the char bed. The flow rate of ash removed was adjusted to 2,8 g/min (i.e. 28 g every ten minutes) in order to keep the bed level constant, and was not changed throughout the experiment.

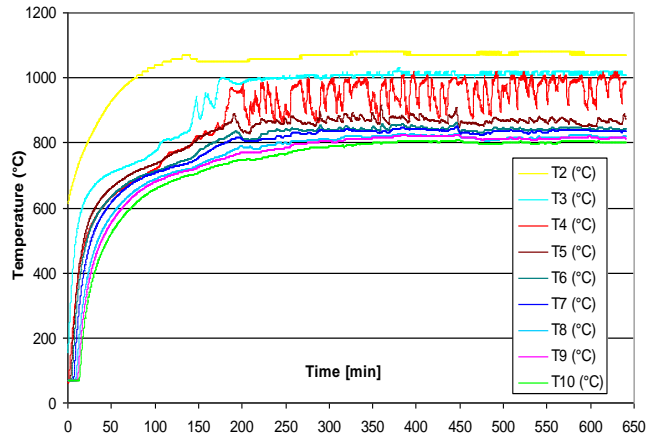


Figure 3: Variation in temperatures during the gasification process

When the steady state regime was achieved, in the reference operating conditions given in table 3, the conversion was higher than 90%. The gas concentrations were constant versus time with a deviation lower than 5%; the mean values are presented in table 4.

Gas	H ₂	CO	O ₂	CH ₄	CO ₂	H ₂ O	N ₂
% (mol)	15.9%	9.8%	0.6%	0.2%	10.8%	9.8%	52.9%

Table 3: Gas concentrations in permanent regime and reference operating conditions.

H₂ and CO concentrations were lower than those encountered in industrial staged or downdraft gasifiers. Heat losses in small reactors are greater and require more energy to reach reaction temperature. Moreover the char was cold when entering in the reactor whereas it is above 500°C in industrial processes. Consequently more energy per kg of char was necessary in our reactor to reach 1000°C at the bed inlet, involving a dilution of the gas produced and in particular of CO and H₂.

From gas concentration measurement and considering the nitrogen flow rate as a tracer, we calculated the flow rates of each gas in order to check a mass balance of the system, which is presented in table 5. The mass balance was very satisfactory, about 3%, confirming the accuracy of our equipment and methodology.

N2	CO2	O2	H2O	char		
169.61	35.76	8.11	54.51	28	g/min	
TOTAL INLET					295.99	g/min
↓						
Char Bed						
↓						
GAS (g/min)		Ashes (g/min)				
N ₂	169.6	bottom	3.2			
H ₂ O	20.3	cyclone	0.13			
O ₂	1.9	total	3.33			
CO ₂	55.2					
H ₂	3.7					
CO	31.8					
CH ₄	0.3					
total gas	282.74					
TOTAL OUTLET					286.07	g/min
↓						
Mass balance					-3.35	%

Table 5: Mass balance

N2	CO2	O2	H2O	char		
3.42	0.77	0.14	2.25	0.87	kW	
TOTAL INLET					7.44	KW
↓						
Char Bed						
↓						
GAS (kW)		Ashes (kW)				
N ₂	2.07	total	0.06			
H ₂ O	8.29					
O ₂	0.02					
CO ₂	-2.18					
H ₂	0.04					
CO	-1.70					
CH ₄	-0.02					
total gas	6.53					
TOTAL OUTLET					6.59	KW
↓						
Energy balance					1.49	%

Table 6: Energy balance

From the experimental results and measurement of gas and particle temperatures and flow rates before and after the bed, heat balances were checked. Energies at the inlet and outlet of the bed were calculated considering the enthalpy of each species at the measured temperature following:

$$\underbrace{+\dot{m}_{char} h_{char} + \sum_j \dot{m}_j h_j}_{Inlet} - \underbrace{\dot{m}_{res} h_{res} - \dot{m}_{fines} h_{fines} - \sum_j \dot{m}_j h_j}_{Outlet} - \dot{Q}_{losses} = 0$$

Where h_j is the specific enthalpy for each compound

$$h_j(T) = h_j^{(0)}(T_0) + \int_{T_0}^T C_{p(j)}(T) dT$$

Where $h_j^{(0)}$ is the standard enthalpy of species j, and $C_{p(j)}$, its specific heat.

Regarding heat losses, we measured the surface temperature on the external wall of the reactor and calculated the heat losses assuming free convection. Char temperature at the bed inlet was assumed to be 520°C as a mean between char temperature at the entrance and gas temperature at the bed inlet. The energy balance was also very satisfactory, with a difference of 2 % between inlet and outlet.

The most important asset of the reactor was its ability to provide profiles of various values along the char bed. The temperature profile from the top (T_2) to the bottom of the reactor (T_8) is presented in figure 4. The temperature of the atmosphere above the char bed (T_4) was quite homogeneous (980 to 1010°C). The temperature measured by T_4 oscillated between 950 and 1000°C as the thermocouple was alternatively inside or outside the char bed.

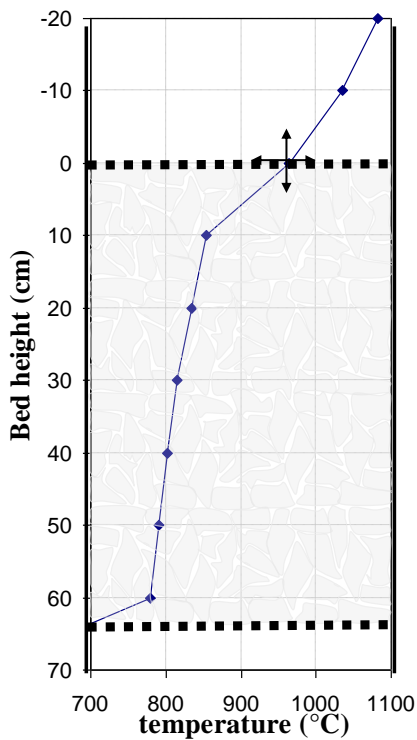


Figure 4: Temperature profile inside the reactor

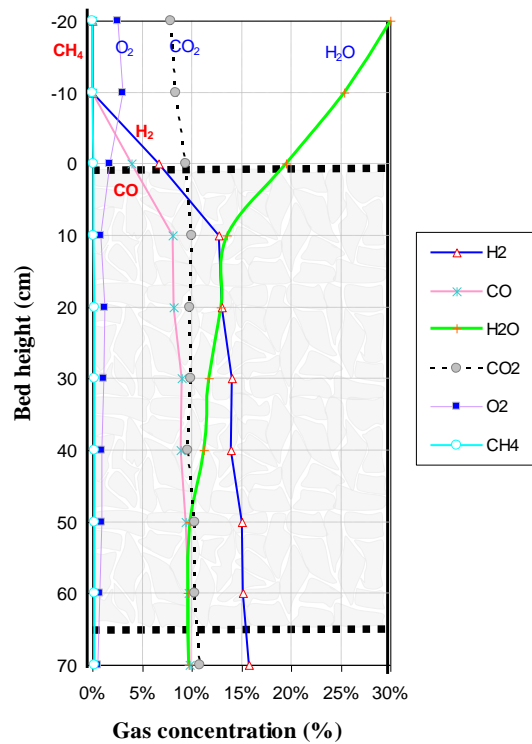


Figure 5: Longitudinal profile of gas composition

At the surface of the bed, the temperature could reach a higher value than that in the reactor atmosphere (1000°C vs. 980°C): this slight overheating was likely to be due to the local combustion of a small quantity of char with the residual O_2 in the burners' exhausts. The temperature inside the bed decreased very rapidly: 850°C at 10 cm from the surface of the bed and slowly through the rest of the bed (55 cm). This observation shows that the main part of the reaction took place close to the bed surface hot zone. Comparable results in terms of temperature profile have been observed by other authors during fixed bed gasification of biomass [6, 7] or coal [4, 13].

The previous comments are confirmed by Figure 5, which shows the axial gas concentration of each gas species. H_2 and CO increased rapidly during the first 10 centimetres to reach about 80% of their final values. Globally, variations in gas concentrations tallied well with temperature profiles confirming the presence of a high reactive zone in the top of the bed where mainly endothermic reactions occurred. Consequently, the H_2O concentration decrease when CO and H_2 increased was relevant regarding steam gasification. Worth noting is the relative stability of CO_2 concentration throughout the bed. In fact, many reactions are in competition in terms of CO_2 presence: the Boudouard reaction consumes CO_2 but char combustion and the water gas shift reaction produces CO_2 so that production and consumption are compensated.

4 CONCLUSION

The purpose of this work was to design and build new experimental equipment to characterise the wood char gasification stage in a fixed bed or staged reactor. Particular attention was paid to the instrumentation, in order to access relevant information such as the temperature, gas composition, carbon conversion and char density all along the char bed. This tool was used to characterise a wood char produced by the pyrolysis step of a 2-stage process. Set-up tests were performed with a view to reaching a stationary regime, i.e. with no variation in temperature, gas composition and bed height. Under operating conditions relevant for industrial gasifiers in terms of temperature and atmosphere bed attack, a conversion rate of 92% was reached. Moreover, the reliability of both the equipment and the methodology was confirmed by the validation of accurate heat and mass balances. Temperature and gas concentration profiles along the bed were presented and showed that gasification mainly took place in the first 10 cm of the bed where more than 80% of the conversion occurred. The next experiments will aim to carry out a complete parametric study in order to provide relevant data for the validation of a char bed model.

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