Gasification of Argan nut shell biomass in throated downdraft gasifier: Shapes of syngas laminar jet diffusion flame

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1 Introduction

Gasification is a thermochemical method that enables the conversion of solid fuels into a gaseous mixture known as syngas or synthesis gas at elevated temperatures (750 – 1500 °C). When used as a fuel, it contributes to reducing greenhouse gas emissions compared to traditional fossil fuels [1]. The makeup of syngas is influenced by several factors, including the biomass type, temperature, and the gasification agent used, which could be air, steam, oxygen, carbon dioxide, or a blend of these. The thermochemical conversion of biomass with a substoichiometric gasification agent (such as air) produces carbon monoxide, hydrogen, small amounts of methane, and by-products like tar, water, and impurities. Consequently, syngas is primarily composed of these substances, along with carbon dioxide, nitrogen, and trace amounts of other compounds.

Gasification can be performed using various types of gasifiers, including fixed-bed (updraft or downdraft), fluidized-bed, entrained-flow, and plasma reactors [2]. Fixed-bed gasifiers, typically used for power outputs below 10 MW, offer high thermal efficiency and require minimal biomass pre-treatment. Their low cost and ease of operation make them well-suited for local electricity generation [3, 4] and for producing cleaner fuels like hydrogen and carbon monoxide with low tar content. In downdraft gasifiers, air and biomass flow downward together, leading to significantly less tar in the syngas compared to updraft designs, where air and biomass move in opposite directions [5, 6]."

Another key factor influencing the gasification process is the specific properties of the biomass. Numerous studies have explored the use of various biomass types [7, 8, 9], including residues from anaerobic digestion plants, municipal waste [10, 11, 12], and waste from sewage sludge of wastewater treatment plants [13].

The composition of syngas significantly impacts combustion systems. Each gas species, including CO (carbon monoxide), H_2 (hydrogen), and CH_4 (methane), plays a crucial role in flame stability. Specifically, the H_2/CO ratio affects various physical and chemical properties; as the CO content increases and the H_2/CO ratio decreases, there is a change in laminar burning velocity [14]. Furthermore, the presence of CO_2 (carbon dioxide) and N_2 (nitrogen) in syngas helps reduce flame flickering instability and flame length for a stable flame [15].

In this study, experiments are conducted to examine how the instantaneous composition of syngas affects flame shape. To achieve this, a downdraft gasifier was designed and built to produce syngas from argan nut shell (ANS) biomass. The objective is to obtain consistent flame-shape measurements in flames burning in quiescent air.

2 Materials and methods

2.1 Biomass characterization

The biomass used for gasification is argan nut shell (ANS) purchased from local factories in the Massa region in Morocco. Particles chosen in the test of this research have the largest dimension which does not exceed 15 mm, which prevents bridging problems. The aspect ratio for particles was between 0.6 and 1.2 and the bulk diameter was 9.12 mm. This size was chosen to eliminate gaps in the biomass bed and ensure smooth gas flow. The main properties of ANS are summarized in Table 1.

Table 1: Ultimate and proximate analysis of ANS biomass

Ultimate analysis (wt%)						Proximate analysis (wt%)					HHV (MJ/kg)
C	H	O	N	S		MS	VM	FC	Ash		
51.33	6.32	42.35	0.05	0		9.5	67.5	21.8	1.5		18.3

A moisture content of 9.5% is close to the acceptable limit (10-20%) for biomass suitable for gasification. Using Carbone as a reference, the ANS's empirical formula is $CH_{1.46}O_{0.62}$, where 1.46 and 0.62 represent the H/C and O/C molar ratios, respectively [16].

2.2 Gasification system

The experimental setup in Fig. 1 includes three main parts: a gasifier, a system to measure temperature and gas composition (with a gas analyzer), and a boiler that burns the produced syngas. The gasifier is a throated downdraft design, constructed from stainless steel, with a thermal power output of 7.5 kW. It has a height of 0.682 m, an inner diameter of 0.190 m, and is lined with a 20 mm thick insulating layer. The throat diameter is 0.047 m. Syngas exits the reduction zone through a grate and flows into a 2.50 m long, 30 mm diameter stainless steel tube, which significantly reduces its temperature. The tube is connected to a syngas cleaning system before the gas is directed to the boiler. Gas sampling was carried out to collect tar and particles using solid filtration and tar absorption in a solvent stored in chilled steel bottles. A small portion of the cleaned syngas was directed to a gas analyzer (X-Stream Emerson) for analysis. Before reaching the analyzer, the sample passed through four filters and was pumped through a gas cooling and cleaning system. The gas composition (H_2, CO_2, CO, CH_4, O_2, N_2) is measured every second by volume. The remaining syngas is sent to the boiler for combustion. Before entering the boiler, part of the syngas is directed to a secondary burner located under a laboratory hood. This burner, a tube with a 9.4 mm inner diameter and 150 mm length, is designed to produce a laminar diffusion flame in quiescent air. Flame images are recorded by a video camera (29.799 frames per second, 3840 × 2160 pixels), and flame temperature is measured using a thermocouple.

The thermal gasification process is monitored by observing the temperature profiles at different locations within the gasifier using Type-K and Type-C thermocouples. Temperatures are recorded every second by a data logger. The analyzer and data logger are connected to a computer for data analysis.

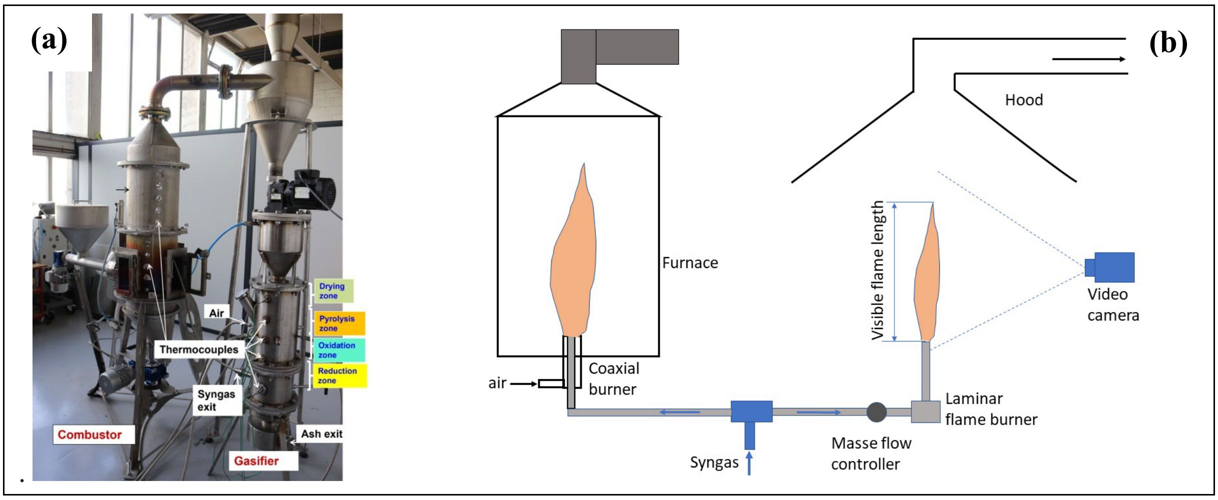


Figure 1: Gasifier and Combustion test rig (a). Schematic diagram of diffusion laminar flame (b).

The oxidizing agent is air, provided by the laboratory compressor, controlled by a mass flow controller, and introduced into the gasifier's oxidation zone through six radial tubes. The stoichiometric air requirement for 1 kg of ANS is 4.75 Nm3/kg based on CHONS analysis. The stoichiometric air-fuel ratio (AFR) was also calculated (6.23 kg-air/kg-fuel), which is the amount of air and fuel for complete combustion. The airflow can be adjusted to achieve the desired equivalence ratio (ER). Gasification experiments were conducted at different ER, but the results presented here only concern ER=0.29.

2.3 Effect of air flow rate (AFR)

Biomass gasifier performance is influenced by the equivalence ratio (ER) that integrates the effects of airflow rate, ANS supply rate, and run duration. The ER for a given run is calculated as follows:

$$ER = \left(\frac{Air\ flow\ rate}{Biomass\ Consumption\ Rate}\right) \Big/ \left(\frac{Air\ flow\ rate}{Biomass\ Consumption\ Rate}\right)_{Stoichiometric}$$

The effect of airflow rate (AFR) on ANS biomass consumption rate (BCR) and equivalence ratio (ER) is shown in Fig. 2. It was observed that as the airflow rate increases, the biomass consumption rate also rises. This increase in the airflow rate provides more oxygen, resulting in a higher amount of biomass being combusted due to the enhanced pyrolysis rate. Additionally, the equivalence ratio (ER) also increases with the airflow rate (AFR).

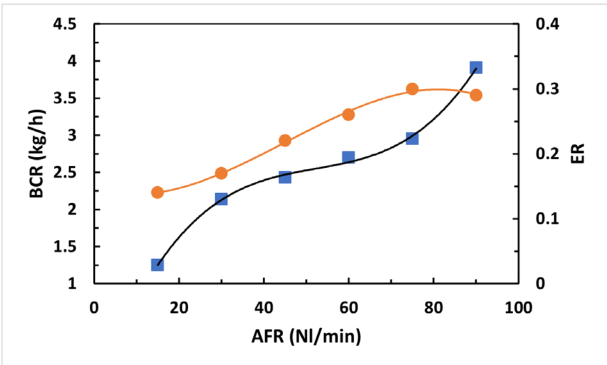


Figure 2: Effect of AFR on ER and ANS BCR

2.4 Experimental apparatus

Before starting the experiments, the bottom part is filled with 300 g of ignited charcoal, and air is supplied for about 3-5 min. When The temperature of the oxidation zone increases above 400 °C, the biomass feedstock is filled until the oxidation zone (0.5 kg). Air is supplied until the temperature of the oxidation zone indicates 850 °C. Then the gasifier is filled with fully biomass feedstock from the hopper and the air is set at the required value corresponding to the desired equivalent ratio. The gasification experiments were conducted at a 0.29 equivalence ratio.

3 Results

The gasification experiment of ANS was conducted at an equivalence ratio (ER) of 0.29 corresponding to a consumption of 2.5 kg of ANS in 2300 seconds (indicated by the gasification zone in Fig. 2.) with an airflow of 90 Nl/min. The temperature profile in different zones of the gasifier (TC1: reduction, TC2: oxidation/combustion, TC3: pyrolysis, TC4: drying, and TC5: gas outlet) and the instantaneous volume of each gas in syngas are presented in Fig. 3., from the startup, ignition of ANS, to its complete consumption. The syngas average gas composition, HHV, and LHV values are presented in Table 2 for ER=0.29. The results of the gasification of olive husk agricultural waste in an updraft gasifier with a capacity of 250 kW [8b] are presented also in Table 2. A comparison is also presented between the composition of the current results and those reported in the literature for olive husk agricultural waste [9], obtained using an up-draft gasifier with a 250 kW capacity. Fig. 3. Also shows the instantaneous density of syngas ρ (kg/m3), calculation is based on syngas composition, which ranges from 0.966 to 1.08 kg/m^3.

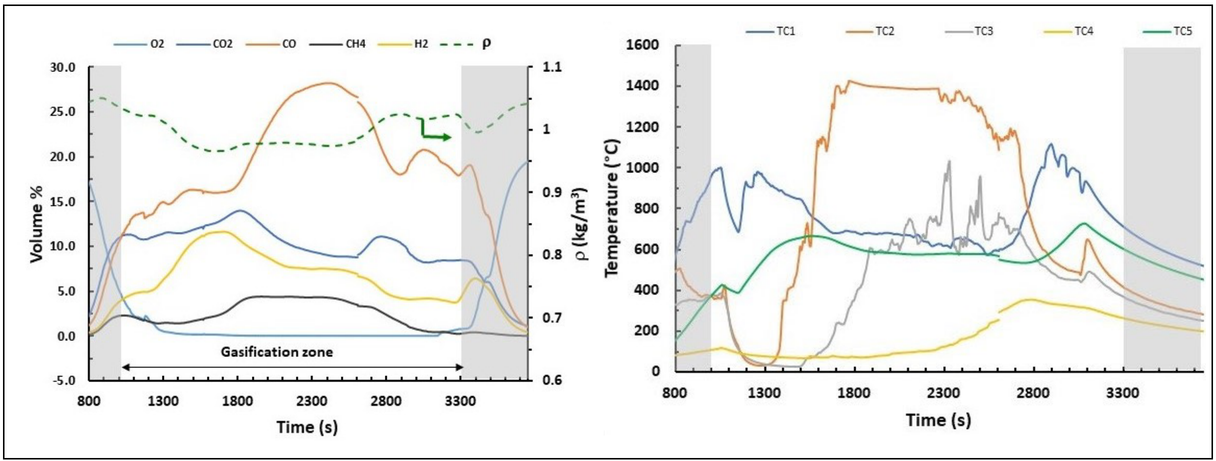
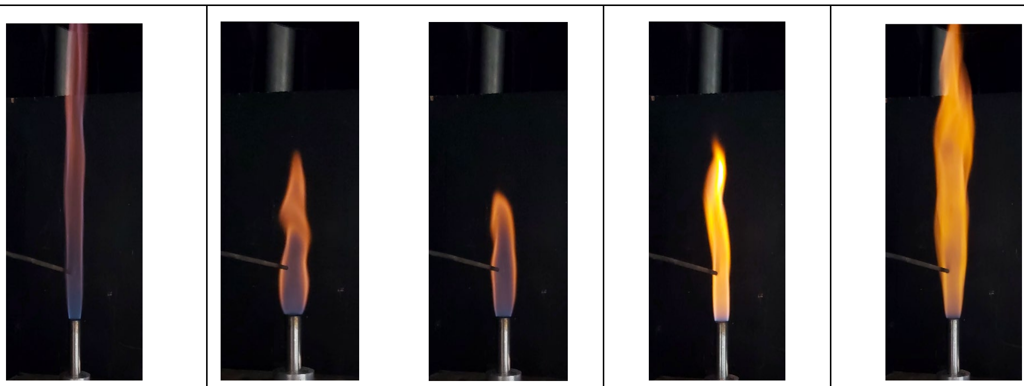


Figure 3: Syngas composition and temperature measurement at different zones in a gasifier

Table 2: Gas composition of producer syngas from ANS biomass gasification at ER=0.29.

Biomass	HHV (MJ/kg)	ER	Average syngas composition (Vol.%)						Syngas HHV (MJ/Nm3)	Syngas LHV (MJ/Nm3)
			CO	CO_2	CH_4	H_2	O_2	N_2		
ANS	18.3	0.29	18.77	8.51	2.24	5.79	3.36	61.37	4.0	3.8
Olive husk [8b]	17.70	0.5	13.9	13.2	2.9	14.1	-	55.9	4.1	-

Figure 4 shows the shapes of the laminar syngas flame at four different times: 1000 s (I), 1167 s (II), 1296 s (III), and 3220 s (IV). The syngas compositions corresponding to these time points are shown in Table 3.



t= 1000 s (I)	t= 1167 s and t= 1168 s (II)	t= 1296 s (III)	t= 3220 s (IV)

Figure 4: Flame images at four instantaneous syngas composition.

Table 3: Instantaneous values of syngas composition and corresponding visible length

Time (s)	CO (Vol%)	CH_4 (Vol%)	H_2 (Vol%)	CO_2 (Vol%)	O_2 (Vol%)	N_2 (Vol%)	Fuel to syngas ratio	ρ (kg/m3)	Lvisible (mm)
1000	10.54	2.25	3.81	10.95	5.12	67.33	16.6	1.10	227 ± 2
1167-1168	13.72	1.74	4.95	10.78	1.83	66.98	20.41	1.11	74 ± 4
1296	14.99	1.46	6.24	11.42	0.54	65.35	22.69	1.11	127± 4
3220	20.08	0.44	4.13	8.40	0.02	66.93	24.65	1.19	221 ± 2

A comparison between cases (I) and (II) reveals that CO and H_2 concentration increase by 30%, while CH_4 decreases by 29.3%, resulting in a 206% reduction in the visible flame length. Here, only the CH_4 concentration is affected, as the H_2/CO ratio remains steady at 0.36, the CO_2 (10%) and N_2 (67%) contents are identical in both cases, and O_2 present in the syngas decreases from 5.12% to 1.83%. The effect of CH_4 on laminar syngas flame lengths was reported by [17].

Between cases II and III, despite a 19% reduction in CH_4 content, the visible flame length increases by 71%. This phenomenon is attributed to an increase in H_2, CO, and the H_2/CO ratio, which rises from 0.36 to 0.41.

When comparing cases (II) and (IV), CH_4 decreased by 295%, CO increased by 46.4%, while H_2 decreased by 19.9%, resulting in a reduction of the H_2/CO ratio from 0.36 to 0.205, and the visible flame length increased by 198%. The combined effect of increased carbon monoxide (CO) and decreased hydrogen (H_2) had a significant impact on the visible flame length.

Conclusion

A single-throat downdraft gasifier using air as the oxidizing agent was developed to produce syngas from argan nut shell biomass. The average composition of the resulting syngas was 18.77% CO, 5.79% H_2, and 2.24% CH_4, with a higher heating value of 4 MJ/Nm³. An instantaneous syngas generator was employed to produce a laminar flame and flame heights were measured to analyze the visible flame lengths corresponding to varying gas composition percentages in the syngas. Although not detailed here, additional syngas parameters—such as effective diffusivity, Schmidt number, and Froude number—were also determined to evaluate the flame's stoichiometric contour.

References

[1] Demirbas A. (2005). Potential applications of renewable energy sources, biomass combustion related environmental issues. Prog. Energy Comb. Sci. 31: 171-192.

[2] Tezer Ö, Karabag N, Öngen A, Colpan CÖ, Ayol A. (2022). Biomass gasification for sustainable energy production -A review. Int. J. Hydrogen Energy. 47: 15419-15433.

[3] Fischer & Pigneri. (2011). Potential for electrification from biomass gasification in Vanuatu. Energy, 36: 1640-1651.

[4] Rahman M, Henriksen UB, Ciolkosz D. (2023). Startup process, safety and risk assessment of biomass gasification for off-grid rural electrification". Scientific Reports 13: 21395.

[5] Sharma PK, Sharma AK, Rose Havilah Pulla RH, Sahoo PK. (2024). Performance analysis of a medium-scale downdraft gasifier using Lantana camera biomass as feeding material. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 46. Issue 1: 15087-1510.

[6] Sutar KB, Kohli S, Ravi M. (2017). Design, development and testing of small downdraft gasifiers for domestic cookstoves. Energy 124:447–60. doi:10.1016/j.energy.2017.02.076

[7] Molino A, Chianese S, Musmarra D. (2016). Biomass gasification technology: The state of the art overview". J. of Energy Chem. 25: 10–25.

[8] Sansaniwal SK, Pal K, Rosen MA, Tyagi SK. (2017). Recent advances in the development of biomass gasification technology: A comprehensive review. Renew. Sustain. Energy Rev., 72: 363-384.

[9] De Philippis P., Scarsella M., De Caprariis B., Uccellari R. (2015). Biomass gasification plant and syngas clean-up system. Energy Procedia, 75:240-245.

[10] Aziz M, Darmawan A, Juangsa FB. (2021). Hydrogen production from biomasses and wastes: A technological review. IJHE 46: 33756-33781.

[11] Aydin ES, Yucel O, Sadikoglu H. (2019). Experimental study on hydrogen-rich syngas production via gasification of pine cone particles and wood pellets in a fixed bed downdraft gasifier. Int. J. Hydrogen Energy 32: 17389-17396.

[12] Lopes EJ, Queiroz N, Yamamoto CI, Neto PR. (2018). Evaluating the emissions from the gasification processing of municipal solid waste followed by combustion. Waste Manag. 73: 504-510.

[13] Spiewak. (2024). Gasification of Sewage Sludge: A Review. Energies 17: 17: 4476.

[14] Zhang W, Chen G, Zhi F, Zhang A, Deng H. (2024). Effect of diluent content and H_2/CO ratio on the laminar combustion characteristics of syngas. Int. J. of Hydrogen Energy 89:703-716.

[15] Piemsinlapakunchon T, Paul MC. (2021). Effect of syngas fuel compositions on the occurrence of instability of laminar diffusion flame. Int. J. of Hydrogen Energy 46: 7573-7588.

[16] Rahib Y, Boushaki T, Sarh B, Chaoufi J. (2021). Combustion and pollutant emission characteristics of argan nut shell (ANS) biomass. Fuel Proces. Tech. 213:106665.

[17] Piemsinlapakunchon T, Paul MC. (2019). Effects of fuel compositions on the heat generation and emission of syngas/producer gas laminar diffusion flame. Int. J. of Hydrogen Energy 44: 18505-18516.