ISSN: 1859-2171
e-ISSN: 2615-9562 TNU Journal of Science and Technology 203(10): 23 - 29

STEAM GASIFICATION OF BAGASSE: EFFECT OF HEATING RATE

Hong Nam Nguyen[1*], **Laurent Van De Steene**[2]
[1]*University of Science and Technology of Hanoi, Vietnam Academy of Science and Technology, Hanoi, Vietnam*
[2]*BioWooEB, CIRAD, Montpellier, France*

ABSTRACT

Bagasse residue is a potential feedstock for steam gasification, but knowledge of this technology is still small and fragmented. Heating rate is of the most important factors influencing the gasification process. However, this parameter has not yet been fully investigated. In this study, the characteristics of bagasse and its chars were identified, and the effect of heating rate on steam gasification kinetics was studied. Bagasse contained little ash content, comparable to woody biomass, which is beneficial for gasification processes. The bagasse char had a high heating value, comparable to coal. Effect of a small change in heating rate from 5 to 15 °Cmin^{-1} was not observed, while a significant increase from 15 to 1800 °Cmin^{-1} had a considerable effect on steam gasification kinetics. A char produced at a high heating rate increased gasification kinetics by 1.35 times compared to a char produced at a low heating rate. Results and data produced could be useful for the conception of new gasifiers using bagasse, such as staged-gasifiers in which the char production zone is separated from the gasification zone.

Keywords: *Bagasse; biomass; steam gasification; kinetics; Macro-thermogravimetric analysis*

Received: 29/7/2019; Revised: 15/8/2019; Published: 16/8/2019

KHÍ HÓA BÃ MÍA VỚI TÁC NHÂN HƠI NƯỚC:
ẢNH HƯỞNG CỦA TỐC ĐỘ GIA NHIỆT

Nguyễn Hồng Nam[1*], **Laurent Van De Steene**[2]
[1]*Trường Đại học Khoa học và Công nghệ Hà Nội, Viện Hàn Lâm Khoa học và Công nghệ Việt Nam, Hà Nội, Việt Nam*
[2]*BioWoodEB, CIRAD, Montpellier, Pháp*

TÓM TẮT

Bã mía là nguồn nguyên liệu tiềm năng cho khí hóa với tác nhân hơi nước, nhưng kiến thức về công nghệ này vẫn còn hạn chế và phân mảnh. Tốc độ gia nhiệt là một trong những yếu tố quan trọng nhất ảnh hưởng đến quá trình khí hóa. Tuy nhiên, thông số này vẫn chưa được nghiên cứu đầy đủ. Trong nghiên cứu này các đặc tính của bã mía cùng than làm từ bã mía đã được xác định, và ảnh hưởng của tốc độ gia nhiệt đến động học của quá trình khí hóa đã được nghiên cứu. Bã mía chứa hàm lượng tro thấp, tương đồng với gỗ nên có lợi trong các quá trình khí hóa. Than làm từ bã mía có nhiệt trị cao, tương đương với than đá. Tốc độc gia nhiệt thay đổi nhỏ từ 5 lên đến 15 °Cmin^{-1} không gây ảnh hưởng tới tốc độ chuyển đổi, trong khi một sự thay đổi lớn từ 15 lên đến 1800 °Cmin^{-1} gây ảnh hưởng đáng kể đến động học khí hóa hơi nước. Than sản xuất ở tốc độ gia nhiệt cao làm tăng tốc độ chuyển hóa lên 1,35 lần so với than sản xuất ở tốc độ gia nhiệt thấp. Kết quả và dữ liệu của nghiên cứu có thể hữu ích cho việc phát triển các hệ thống khí hóa mới sử dụng bã mía, ví dụ như các hệ thống khí hóa nhiều tầng có tầng làm than được tách biệt với tầng khí hóa.

Từ khóa: *Bã mía, sinh khối, khí hóa với tác nhân hơi nước, động học, phương pháp phân tích nhiệt vĩ mô*

Ngày nhận bài: 29/7/2019; Ngày hoàn thiện: 15/8/2019; Ngày đăng: 16/8/2019

* Corresponding author: *Email: Nguyen-hong.nam@usth.edu.vn*

https://doi.org/10.34238/tnu-jst.2019.10.1873

1. Introduction

Sugarcane is widely grown in various regions in the world, with a global production of 1.9 billion tons in 2016 [1]. The sugar extraction from this crop generates a huge amount of sugarcane bagasse, estimated at 0.5 billion tons of bagasse, i.e. 0.27 tons of bagasse for each ton of sugarcane [2]. This residue is often used inefficiently in low-value applications such as direct burning for cooking, building material, and animal husbandry, or is burned as a simple way to get rid of it [3]. For this reason, in view of the solid wastes generated, the sugar industry is considered one of the most polluting industries. Sugarcane bagasse, however, has high potential to be used as a fuel for efficient energy processes, such as gasification. This is also a relevant solution to minimize pollution to a large extent, as well as creates added-values for this industry.

Gasification is a thermochemical conversion process that converts carbonaceous fuels into syngas, a mixture of mostly carbon monoxide (CO) and hydrogen (H_2), and a small amount of carbon dioxide (CO_2), methane (CH_4) and nitrogen (N_2) [4]. Syngas can be used to produce heat, electricity or transport fuel. Gasification involves a series of sub-processes, namely drying, pyrolysis, and char gasification. Currently, wood is the most common feedstock for biomass gasification [5]. With the environmental concerns of using woody biomass, diversifying the feedstock is among the first priorities for this technology. Air/oxygen, carbon dioxide or steam can be used as reactive gases in a gasification process. Among them, steam gives the most volume of Hydrogen in the syngas, which is more beneficial for high-end usages such as transportation fuels or electricity production.

Two most important factors that affect a gasification process are (1) the properties of the feedstocks and (2) the operating parameters. Di Blasi stated that the gasification reactivity of biomass varied significantly [6]. For example, at a temperature of 1000K, the reactivity between different types can differ by a ratio of 10^4 for steam gasification. This means that results from one biomass cannot be extrapolated to another, but can only be used for comparison. The physicochemical characteristics of biomass strongly influence gasification characteristics [7]. To date, only a few studies have been conducted on bagasse as biomass feedstock for gasification.

In addition, a number of operating parameters can affect the gasification of biomass, such as gasifying temperature, partial pressure of the reacting gas, and heating rate [8]. Among them, the heating rate is particularly important. In most of the existing design, biomass feedstocks in their original form are directly injected to the gasification system. Inside the reaction zone, biomass will be dried, pyrolyzed, and then gasified to get the syngas. This method, however, makes the quality control of output gas very difficult because it is highly dependent on the characteristics of the biomass. Recently, some staged-gasifiers have been developed with the aim of controlling better the characteristics of the feedstock being injected into the system. Biomass will firstly be pyrolyzed in a separated zone, then the biochar produced will be injected to the gasification zone. In this design, the heating rate plays a crucial role in shaping the properties of biochar. The heating rate was proved to have a significant impact on gasification kinetics [9]. Depending on the heating rate, biochars will have different characteristics and will react differently with reactive gases during the process [5], [10], [11]. Detailed knowledge of the impact of the heating rate to the steam gasification kinetics is thus essential for the selection of optimal gasification conditions, as well as for the design of new reactors or the improvement of existing ones. Up to date, no reference for the effect of heating rate on gasification of bagasse has been reported in the literature.

The objective of this study was thus to (1) characterize the properties of bagasse and its chars, produced at different heating conditions and (2) study the influence of heating rate on the gasification kinetics of bagasse char.

2. Material and method

2.1. Bagasse feedstock

Sugarcane bagasse, widely available in the North of Vietnam was selected for this study. The sample was crushed and sieved to collect the particles size of less than 1.0 mm. The moisture content was firstly determined following the ASTM E1756 – 08 standard. Biomass feedstock was then cleaned with distilled water to remove dust and impurities, and dried in the oven (Memmert Model 800 Class B) at 105°C for 24 hours to remove their moisture content. The biomass samples were then stored in air-tight boxes at room temperature for further analyses.

Proximate (volatile matter, fixed carbon, and ash contents), ultimate (Carbon (C), Hydrogen (H), Nitrogen (N), Sulfur (S) and Oxygen (O) contents), and calorific values were conducted to characterize biomass feedstock. The volatile matter was determined following the ASTM D 3175 – 07 standard. The ash content was determined following the ASTM D 3174-04 standard. The fixed carbon content was calculated by difference. The higher heating value of biomass feedstocks was evaluated using the Parr 6200 Calorimeter, following the procedure described in the NREL protocol. The Carbon (C), Hydrogen (H), nitrogen (N), Sulfur (S) and Oxygen (O) contents of biomass samples were determined using the PerkinElmer 2400 Series II Elemental Analyser.

2.2. Bagasse char preparation

For bagasse chars produced at low heating rates (5°Cmin^{-1} and 15°Cmin^{-1}) the muffle furnace (Nabertherm brand) was used (Figure 1).

About 400 g of baggage was placed in an airtight refractory steel box, 25 cm in diameter and 20 cm in height. The box was swept with N_2 to avoid oxidation, placed in the muffle furnace. The furnace was heated to a final temperature of 850 °C and maintained for 30 minutes. To study the effect of heating rate on gasification conversion, another char was produced at the high heating rate of 1800 °Cmin^{-1}, using the macro-thermogravimetric reactor described below. Proximate and ultimate analyses of these chars were also conducted.

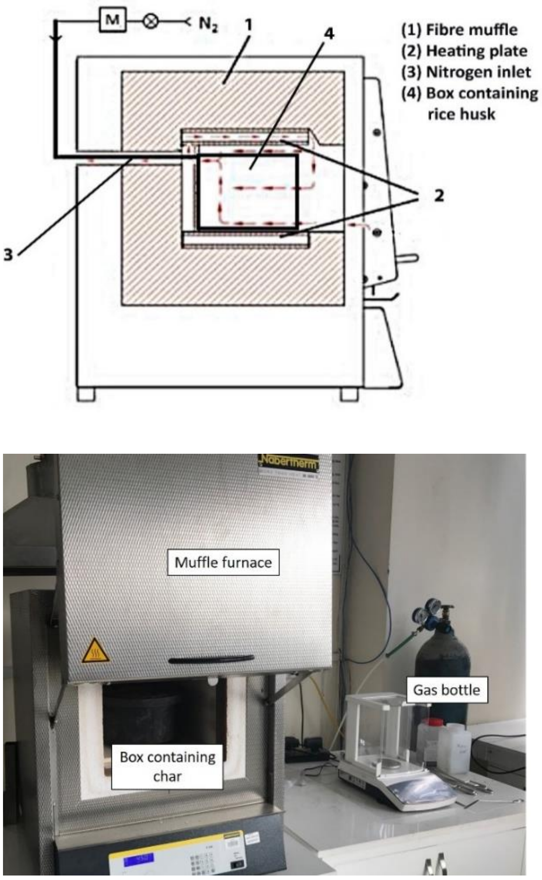

Figure 1. *Muffle furnace for char production*

2.3. Experimental setup

A macro-thermogravimetric reactor was designed and set up for this study (Figure 2).

The reactor consisted of a ceramic tube, 111 cm in length, with an internal diameter of 7.5 cm (1), placed in an electrical furnace (2). Heating was ensured by three independently controlled heating zones, ensuring the temperature was uniform throughout the reactor. The reaction atmosphere was generated by a mixture of N_2 and steam. Each gas was controlled by a mass flowmeter. The gas mixture was preheated in a 2 m long coiled tube (3) located in the upper heated part of the reactor.

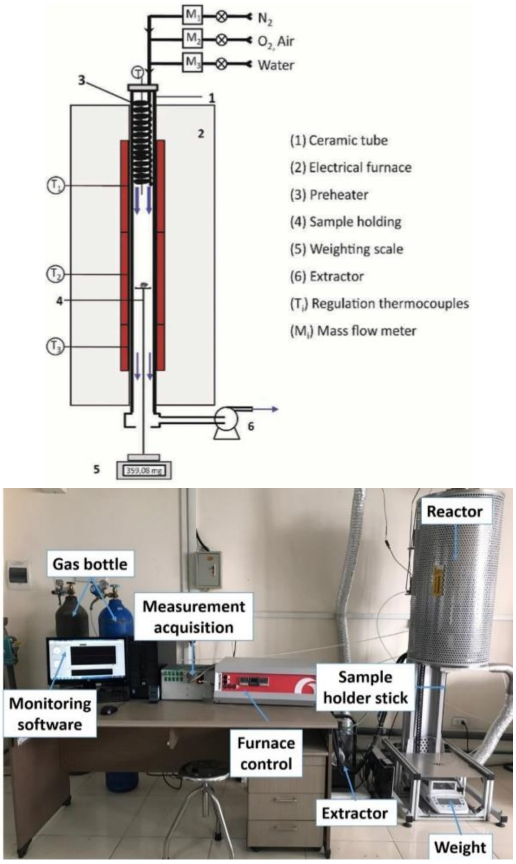

Figure 2. *Muffle furnace for char production*

The experiment consisted of gasifying bagasse char at atmospheric pressure, at 850 °C and 20% of steam. Sample mass was measured and recorded continuously. Conversion X during gasification was calculated as follows:

$$X = \frac{m_i - m}{m_i - m_{ash}}$$

where m_i, m, and m_{ash} are respectively the initial mass, the mass at time t and the mass of ash. All experimental data presented in the following are the average of at least two replications.

3. Results and discussion

3.1. Characteristics of bagasse and chars

The characteristics of bagasse and its chars produced at different heating rates were given in Table 1. Bagasse had a high moisture content of 19.11% that could strongly affect thermal conversion processes. High moisture reduces the temperature in the system, resulting in the incomplete conversion of biomass feedstock and/or other operational problems. Moisture above 10 % is usually not preferred in the thermochemical conversion process [12]–[14]. Therefore, bagasse is highly recommended to be dried before using feedstocks for any energy conversion process.

Volatile matter of bagasse was high, which could be an advantage for thermal chemical conversion processes: chemical energy is stored mainly in the form of fixed carbon and volatile matter, which can be released during thermal degradation. The ash content of bagasse was not significant, indicating that it is particularly well suited for thermochemical conversion processes. The higher heating value (HHV) of bagasse was 16.5 $MJkg^{-1}$, comparable to half of the coal generally [15].

Table 1. *Proximate analysis of bagasse and its chars*

Sample	Moisture (% wt)	Proximate analysi (% wt, db)			HHV ($MJkg^{-1}$, db)
		V	A	FC	
Bagasse	19.11	84.08	0.7	15.22	16.45
Char (5°$Cmin^{-1}$)	-	3.05	4.27	92.80	29.95
Char (15°$Cmin^{-1}$)	-	2.45	4.29	93.37	29.90
Char (1800°$Cmin^{-1}$)	-	1.55	4.33	94.24	27.50

V: Volatile matter, A: Ash content, FC: Fixed-carbon content, HHV: Higher heating value, db: dry basis.

Table 2. *Ultimate analysis of bagasse and its chars*

Biomass	Ultimate analysis (% wt, daf)					Atomic ratios	
	C	**H**	**O**	**N**	**S**	**H/C**	**O/C**
Bagasse	45.55	7.43	46.87	0.09	0.06	1.96	0.77
Char (5°Cmin^{-1})	68.78	4.56	26.17	0.45	0.04	0.80	0.29
Char (15°Cmin^{-1})	67.59	4.65	27.27	0.45	0.04	0.83	0.30
Char (1800°Cmin^{-1})	66.95	4.23	28.34	0.43	0.05	0.76	0.32

C: Carbon, H: Hydrogen, O: Oxygen, N: Nitrogen, S: Sulfur, daf: dry-ash-free basis.

Regarding bagasse chars, it had similar proximate results, despite differences in heating rate during char formation. The heating rate of bagasse char was high, comparable to coal. A slight decrease in the heating value was in char was observed at the char produced at high heating rate. This may slightly affect the gasification process, as more feedstock needs to be introduced to the system to produce the same amount of energy.

Regarding the ultimate analysis results (Table 2), the content of C was significantly decreased when bagasse was turned into chars, while the content of H slightly decreased. Therefore, the H/C and O/C atomic ratios were also decreased. A small amount of N and S was trapped into biomass during the growth. These contents in all biomass feedstocks were very low–therefore the potential for NO_x and SO_x emissions from bagasse is also negligible. Ultimate results are particularly important to calculate the stoichiometry of reactive gases that need to be injected into the system.

3.2. Influence of heating rate to steam gasification kinetics

Heating rate is known to have an influence on the morphology of the char obtained, and hence on its reactivity during gasification [9]. In this study, the influence of heating rate to steam gasification kinetics was investigated in the range of 5 to 1800°Cmin^{-1}. High values of heating rate can be found in a fluidized bed, or in the case that a particle enters into contact with a heated wall. Gasification conditions were as follows: 1 atm, 850 °C and 20% of steam. These conditions were relevant to those that exist in industrial gasification systems [9]. The result is reported in Figure 3.

Gasification of bagasse chars produced at low heating rates finished after 3900 s. It can be seen that for chars produced at low heating rates of 5°Cmin^{-1} and 15°Cmin^{-1}, the difference in gasification kinetics was not significant. Meanwhile, for the char produced at 1800°Cmin^{-1}, gasification was complete after 2900 s. The gasification rate was thus about 1.35 times faster with a char produced at 1800°Cmin^{-1} than with a char produced at 15°Cmin^{-1}. This means that depending on the way the bagasse char was prepared, the char conversion rate during gasification can vary with a ratio of 1.35. This information is very important if one considers a staged-gasification system: it is more beneficial to heat the pyrolysis zone to a high temperature before injection of feedstock, so that the char reactivity can be enhanced.

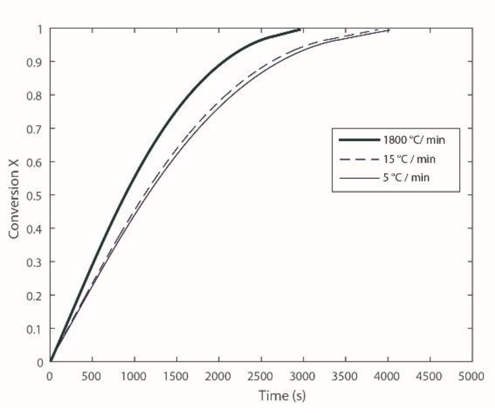

Figure 3. *Influence of heating rate on gasification kinetics*

The effect of heating rate on bagasse char gasification seems to be less important compared to results obtained with wood char gasification reported in the literature: a more difference in reaction kinetics was found between chars produced at different heating rates of 2.6°Cmin^{-1}, 12°Cmin^{-1} and 900°Cmin^{-1} [9].

In the study of Mermoud et al. [9], the pore surface area of wood char produced at 2.6 °Cmin^{-1} was 106 m^{2}g^{-1} compared to 120 m^{2}g^{-1} of wood char produced at 900°Cmin^{-1}. Therefore, the specific surface area of chars produced at high heating rates was more important, resulting in a higher reactivity of the char.

4. Conclusion

The characteristics of bagasse and its chars were determined for the use in steam gasification. Bagasse had a high volatile matter and low ash content, which is suitable for the use as feedstock in gasification processes. Bagasse chars had high calorific values, comparable to those of coal. The influence of heating rate during bagasse gasification in an H_2O atmosphere was also investigated using a macro-thermogravimetric reactor. A significant increase in pyrolysis heating rate enhanced bagasse gasification kinetics. A char produced at a heating rate of 1800°Cmin^{-1} accelerated about 1.35 times the kinetics compared to a char produced at 15°Cmin^{-1}. The experimental database could help researchers or engineers optimize the gasification or the design of new prototypes, such as staged-gasifiers.

Acknowledgement

This research is funded by the University of Science and Technology of Hanoi (USTH) under grant number USTH.EN.01/19-20. The authors would also like to acknowledge the support provided by CIRAD for analysis of samples.

REFERENCES

[1]. "Global sugar cane production 2016-2027," *Statista*. [Online]. Available: https://www.statista.com/statistics/445636/global-sugar-cane-production-forecast/. [Accessed: 21-Jul-2019].

[2]. J. Nikodinovic-Runic, M. Guzik, S. T. Kenny, R. Babu, A. Werker, and K. E. O Connor, "Chapter Four - Carbon-Rich Wastes as Feedstocks for Biodegradable Polymer (Polyhydroxyalkanoate) Production Using Bacteria," in *Advances in Applied Microbiology*, Vol. 84, S. Sariaslani and G. M. Gadd, Eds. Academic Press, pp. 139–200, 2013.

[3]. A. Bhatnagar, K. K. Kesari, and N. Shurpali, "Multidisciplinary Approaches to Handling Wastes in Sugar Industries," *Water. Air. Soil Pollut.*, Vol. 227, No. 1, p. 11, Dec. 2015.

[4]. P. C. Jared and J. M. John, "Benchmarking Biomass Gasification Technologies for Fuels, Chemicals and Hydrogen Production," Jun. 2002.

[5]. L. Van de steene, J. P. Tagutchou, F. J. Escudero Sanz, and S. Salvador, "Gasification of woodchip particles: Experimental and numerical study of char–H2O, char–CO2, and char–O2 reactions," *Chem. Eng. Sci.*, Vol. 66, No. 20, pp. 4499–4509, Oct. 2011.

[6]. C. Di Blasi, "Combustion and gasification rates of lignocellulosic chars," *Prog. Energy Combust. Sci.*, Vol. 35, No. 2, pp. 121–140, Apr. 2009.

[7]. P. Prakash and K. N. Sheeba, "Prediction of pyrolysis and gasification characteristics of different biomass from their physico-chemical properties," *Energy Sources Part Recovery Util. Environ. Eff.*, Vol. 38, No. 11, pp. 1530–1536, Jun. 2016.

[8]. J. P. Tagutchou, L. Van de steene, F. J. Escudero Sanz, and S. Salvador, "Gasification of Wood Char in Single and Mixed Atmospheres of H2O and CO2," *Energy Sources Part Recovery Util. Environ. Eff.*, Vol. 35, No. 13, pp. 1266–1276, Jul. 2013.

[9]. F. Mermoud, S. Salvador, L. Van de Steene, and F. Golfier, "Influence of the pyrolysis heating rate on the steam gasification rate of large wood char particles," *Fuel*, Vol. 85, No. 10, pp. 1473–1482, Jul. 2006.

[10]. M. Zhai, Y. Xu, L. Guo, Y. Zhang, P. Dong, and Y. Huang, "Characteristics of pore structure of rice husk char during high-temperature steam gasification," *Fuel*, Vol. 185, No. Supplement C, pp. 622–629, Dec. 2016.

[11]. K. Xu *et al.*, "Study on Char Surface Active Sites and Their Relationship to Gasification Reactivity," *Energy Fuels*, Vol. 27, No. 1, pp. 118–125, Jan. 2013.

[12]. J. S. Tumuluru, J. R. Hess, R. D. Boardman, C. T. Wright, and T. L. Westover, "Formulation, Pretreatment, and Densification Options to Improve Biomass Specifications for Co-Firing High Percentages with Coal," *Ind. Biotechnol.*, Vol. 8, No. 3, pp. 113–132, Jun. 2012.

[13]. A. Demirbas, "Combustion characteristics of different biomass fuels," *Prog. Energy Combust. Sci.*, Vol. 30, No. 2, pp. 219–230, Jan. 2004.

[14]. B. M. Jenkins, L. L. Baxter, T. R. Miles, and T. R. Miles, "Combustion properties of biomass," *Fuel Process. Technol.*, Vol. 54, No. 1, pp. 17–46, Mar. 1998.

[15]. P. Tan, C. Zhang, J. Xia, Q.-Y. Fang, and G. Chen, "Estimation of higher heating value of coal based on proximate analysis using support vector regression," *Fuel Process. Technol.*, Vol. 138, pp. 298–304, Oct. 2015.

[16]. R. Zhang, Y. Chen, K. Lei, and D. Liu, "The effects of specific surface area and ash on char gasification mechanisms in the mixture of H2O, CO2, H2 and CO," *Fuel*, Vol. 209, pp. 109–116, Dec. 2017.

[17]. A. Zoulalian, R. Bounaceur, and A. Dufour, "Kinetic modelling of char gasification by accounting for the evolution of the reactive surface area," *Chem. Eng. Sci.*, Vol. 138, pp. 281–290, Dec. 2015.