Rice Husk Gasification: from Industry to Laboratory

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Rice Husk Gasification: from Industry to Laboratory

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Abstract. Rice husk gasification (RHG) has been increasingly paid attention in rice-producing countries. Nevertheless, information related to this technology remains small and fragmented. In this paper, the status of RHG has been summarized, highlighting domestic and industrial applications, as well as a scientific review. Moreover, an experimental parametric study was performed to measure: a) the influence of temperature and heating rate on RH pyrolysis, and b) the role of temperature, partial pressure, and heating rate on RHG, under H_2O or CO_2 atmosphere. Regarding pyrolysis, an increase in the final pyrolysis temperature lowers the RH char yield but does not have much effect on the char morphology. Regarding gasification, an increase in the reaction temperature from 900 to 1000 ℃ accelerates about 4.8 and 7 times the char conversion rate, under 0.2 atm of CO_2 or H_2O, respectively. The conversion rate decreases about 1.8 times when CO_2 partial pressure decreases from 1 to 0.2 atm, and about 1.6 times when H_2O partial pressure decreases from 0.4 to 0.1 atm. At 900 ℃ and 0.2 atm, steam gasification was about 3.5 times faster than Boudouard reaction.

1. Introduction

Rice has been grown in more than 75 countries with a world paddy production of 747 million tons in 2016 [1]. This would result in approximately 149 million tons of rice husk (RH), considering a ratio of 0.2 ton of RH for each ton of paddy. While RH has been traditionally used in low-value applications, its potential as a feedstock to generate heat and electricity is attracting increasing attention.

Biomass gasification is a thermochemical conversion process that converts biomass into a CO and H_2 rich-gas called syngas. This latter can be used to produce heat, electricity or fuel transportation. Some different generic types of gasifiers have been developed and commercialized: fixed bed, fluidized, entrained flow and multi-stage gasifier [2]. Gasification involves a series of processes, namely drying, pyrolysis, volatiles oxidation/cracking, and char gasification. Char gasification is particularly important as it controls the syngas production, the complete carbon conversion and thus the efficiency of the whole process. The main reactions involved during char gasification are the following:

$$C + H_2O \rightarrow CO + H_2 \text{ (Steam gasification)} \quad (1)$$
$$C + CO_2 \rightarrow 2CO \text{ (Boudouard reaction)} \quad (2)$$

Currently, wood is principally used for gasification. However, regarding socio-economic issues, diversifying the feedstock is becoming the biggest challenge for this technology. RH gasifiers are increasing rapidly in number in rice-producing countries [2], [3]. Nevertheless, information about current applications and development trends have been small, fragmented and difficult to check. In this context, the first objective of this study was to establish an updated state of the art of rice husk gasification (RHG) to provide a new insight on both industrial and scientific issues. Concerning scientific studies, most of the authors focus on a pilot scale with the aim of evaluating and validating their own designs. Meanwhile, fundamental studies of RHG exist but in a very low number [4]–[7], highlighting a scientific need for further investigation in that field. Therefore, the second objective of this work was to conduct a fundamental parametric study on RHG to provide relevant data on the features of RH pyrolysis, steam gasification, and Boudouard reaction. Results and data produced could be useful to set up industrial or academic codes, necessary for the conception of new RH gasifiers.

2. State of the art of RHG

2.1. Existing technologies and applications

2.1.1. RH gasifier stoves for domestic applications

RH gasifier stoves (Figure 1) have been developed for decades in developing countries for cooking. Most of these gasifiers are based on “top-lit updraft” principle. Firstly, the fuel burns because of primary air supplied to the lower side of the stove. Secondly, the gases released are burned in a flame on the top of the stove, where the secondary air is injected. This design is known to generate less harmful emissions than traditional stoves. Many local manufacturers are positioned in this market with their own designs. Thus, the product efficiency varies greatly from one to another. RH gasifier stoves do not differ much from wood gasifier stoves. Considering the rice husk, small design changes are required to take into account of the specific features of this feedstock, such as high ash content and low density.

Regarding on-going development, several designs have been tested to combine cooking and biochar production [8]. The upscaling of gasifier stoves for more heat demanding applications (collective cooking or small industry) is an interesting development path for this technology. In these cases, the continuous operation of the gasifier is the main challenging issue.

2.1.2. RH gasifiers for heat production

Regarding existing commercial gasifiers, downdraft fixed-bed is the most widespread technology for heat application (Figure 2). The main reasons lie on its simplicity in design and affordability in price. These gasifiers are most common in rice mills to use RH generated by the milling process. It is noteworthy that rice mills can be self-sufficient in terms of energy by using RHG [3]. Heat produced from RH gasifiers can be used for drying, bricks/ceramic cooking, or any processes requiring steam.

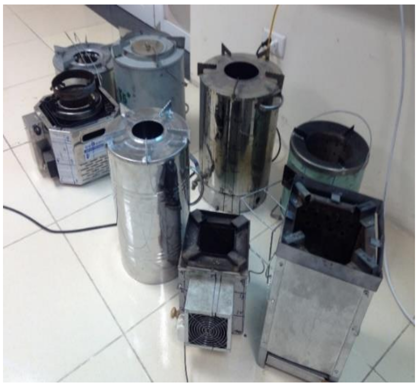


Figure 1. Various designs of RH gasifier stoves in Vietnam (Picture taken by author)

Figure 2: A RH gasifier for heat generation

(Source: https://hayvip.com)

Figure 3: RH gasifier for power generation in Cambodia (Picture taken by author)

The technical constraints of these gasifiers are minor. When a RH gasifier is used for direct heat, there is no need to cool down the syngas, neither does the tar have to be removed. Therefore, these systems do not require expensive gas cleaning equipment. Thermal power of these gasifiers is generally small or medium to match with the local resource availability, and/or the heat required by end-users.
Considering the price of the product and the needs of users, the gasification technology for heat production is quite mature. There are possibilities to improve the efficiency of the system or the quality of the gas, but the main challenge concerns the improvement of the lifespan of the gasifier.

2.1.3. RH gasifiers for power generation
India, China, Myanmar, and Cambodia are the leading countries with dozens of installed gasifiers for power generation (Figure 3). Some other countries start to import and develop the technology, such as Indonesia, Bangladesh, Nepal, and the Philippines, but the number of installed units remains weak. A few power plants using RHG have also been identified in India, Thailand, Cambodia, and Myanmar.
Many international manufacturers produce biomass gasifiers for power generation, but as far as we know, only a few of them provide gasifiers that can really operate with RH. Table 1 summarizes the list of main international manufacturers of RH gasifiers by countries.

Table 1. Main international manufacturers by countries

Country	Manufacturer	Technology
China	Qingdao Kexin New Energy Technology Co. Ltd.	Downdraft fluidized bed
	Weifang Haitai Power Machinery Co., Ltd.	Downdraft fluidized bed
	Hefei Debo Bioenergy Science & Technology Co., Ltd.	Downdraft fixed-bed
	Zhengzhou Haoqili Machinery Co., Ltd.	Downdraft fluidized bed
	Shangqiu Haiqui Machinery Equipment Co., Ltd.	Downdraft fixed-bed
	Wuxi Teneng Power Machinery Co., Ltd.	Circulating fluidized bed
India	Agro Power Gasification Plant Pvt. Ltd.	Downdraft fixed-bed
	S. S. Fabrication	Downdraft fixed-bed
	Urja Gasifiers Pvt. Ltd.	Downdraft fixed-bed
	The Energy and Resources Institute (TERI)	Downdraft fixed-bed
	Ankur Scientific Energy Technologies Private Limited	Downdraft fixed-bed
Japan	Yanmar Co, Ltd.	Downdraft fixed-bed
USA	PRM Energy Systems, Inc.	Updraft fixed-bed
Singapore	Trillion Gasifier	Downdraft fixed-bed

RH gasifiers for power generation are generally of downdraft fixed-bed type. Gasifiers are coupled either with a gas engine or a dual-fuel engine. Such this coupling is very demanding regarding gas quality, as no tars and particles can be injected into the engine. Cyclones and scrubbers are the most common gas cleaning equipment to remove tars and particles. This solution is simple and cheap, but produces wastewater in large quantities, causing serious environmental issues [3].
Development orientations focus on introducing technologies other than fixed-bed to the market, in the objective to provide a better gas quality and to improve the size of the system.

2.2. Pilot and laboratory studies
The scientific literature relates to works in RHG both at the pilot and laboratory scale. Regarding studies on a pilot scale, the authors mainly performed experiments to evaluate the performance of their gasifier when using RH [9]–[13]. In most cases, the technologies remain classical (fixed or fluidized bed type) and none clearly highlights a specific innovation. Information about innovative designs is probably kept confidential for commercialization. Therefore, studies at the laboratory scale have made a greater scientific contribution by providing knowledge and deeper understanding regarding RHG.
Zhai et al. [4] conducted pyrolysis experiments of RH in a fixed-bed gasifier and showed that an increase in final pyrolysis temperature from 600 to 1400 ℃ influences significantly porosity and surface area: the latter presenting a maximum value at 1000 ℃. Moreover, a char produced at high

temperature is less reactive to H_2O during gasification. RH char gasification under H_2O and CO_2 atmosphere has been investigated by Bhat et al. [7] using either RH particles or fine powder. However, the results regarding reaction kinetics remain questionable when compared with the literature [14]. The effect of operating conditions on Boudouard reaction has been studied by few authors [5], [6]. Results showed that temperature strongly influences gasification kinetics. An increase from 750 to 850 ℃ leads to a reduction of 9 times in the reaction rate [5], and 7.5 times when temperature increases from 850 to 950 ℃ [6]. The partial pressure of reacting gas is shown to have a slight influence on conversion. The reaction rate increases 1.2 times when CO_2 partial pressure increases from 50 to 100% [5], and 1.5 times from 25 to 100% [6]. Meanwhile, low pyrolysis heating rate (HR) varying in the range of 5 – 20 ℃.min^{-1} has no effect on RH char gasification kinetics [5]. Regarding kinetic model, the modified random pore model is shown to be suitable to describe the RH char gasification with CO_2. Given the low number of articles found in the literature, there is actually no complete parametric study for RHG under CO_2 and H_2O. Meanwhile, results of existing studies focus mainly on a microscopic scale, making it difficult to apply to real particles behaviour in a gasifier. For this reason, we carried out an experimental parametric study of RHG under H_2O and CO_2 atmosphere at particle scale.

3. Experimental study

3.1. RH feedstock

The RH used for experiments was the popular "Te do", taken from the Red River Delta, Vietnam. Its composition is given in Table 2.

Table 2. Composition of "Te do" RH

M%	VM_{db}%	A_{db}%	FC_{db}%	HHV (MJ/kg)
10.0	64.6	16.4	19.0	15.1

M: Moisture (as received), VM: Volatile matter, A: Ash, FC: Fixed carbon, HHV: higher heating value, db: dry basis.

3.2. RH char preparation

For the purpose of the study, five different chars were produced by varying the HR (5, 20 and 1800 ℃.min^{-1}) and the final temperature T_{final} (600, 750 and 900 ℃). About 400 mg of RH were placed in an air-tight refractory steel box of 25 cm diameter and 20 cm height. The box was swept with N_2 to avoid oxidation and placed in the muffle furnace. Note that this system allowed us to produce a big quantity of char that will be used for the char gasification study. The T_{final} and HR of the furnace were controlled. For the char produced at high HR, i.e. 1800 ℃.min^{-1}, we used the macro-thermogravimetric reactor described below. Whatever the pyrolysis reactor used, the T_{final} was maintained for one hour.

3.3. Experimental setup

A new macro-thermogravimetric reactor was set up to experiment char gasification kinetics (Figure 4).

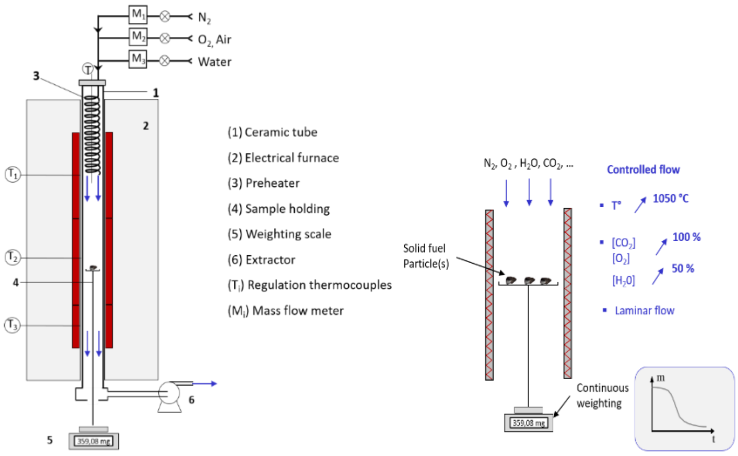


Figure 4. Macro-thermogravimetric reactor and its principle

It consists of a 111 cm long, 7.5 cm i.d. ceramic tube (1), inserted in an electrical furnace (2). The heating is ensured by three independently controlled heating zones, allowing a uniform temperature along the reactor. The reaction atmosphere is generated by a mixture of N_2 and a reacting gas (H_2O, O_2, air or CO_2) in selected proportions. Each gas is controlled by mass flowmeters (M_1, M_2, and M_3). The gas mixture is preheated in a 2 m long coiled tube (3) located in the upper part of the reactor.
The experiment consists of gasifying RH char particles at atmospheric pressure, in a well-controlled atmosphere in terms of temperature and partial pressure of reacting gas. Sample mass was measured and recorded continuously. For each experiment, the reactor was first heated to the desired operating temperature. Then the sample holding (4) containing char particles was lifted from the bottom of the reactor to the desired position and maintained under N_2 to release all remaining VM. When a constant mass was achieved, gas flows were established. As gasification took place, the mass of the char progressively decreased until constant mass - that corresponded to the ash content - was obtained.
The conversion X during gasification was calculated as follows:

$$X = \frac{m_i - m}{m_i - m_{ash}} \tag{3}$$

where m_i, m, and m_{ash} are respectively the initial mass, the mass at time t and the mass of ash.
The gas flow rate of 5Nl.min^{-1} and the samples of 100 mg were chosen for all experiments. We previously checked that these values allowed gasification to take place in a chemical regime. A deviation of less than 10% in measurements was observed, which is acceptable considering the HR heterogeneity and equipment accuracy [15]. All the data below are an average of at least 2 repeatability experiments.

3.4. *Pyrolysis of RH*

3.4.1. Influence of temperature

Pyrolysis experiments were performed (Table 3) considering 3 T_{final} of 600, 750 and 900 ℃ and the same HR of 20 ℃.min^{-1} for this study. RH char yield slightly decreases with an increase in T_{final}, from 39.5% at 600 ℃ to 36.6% at 900 ℃. As a consequence, the ash content in the char is increasing accordingly.

Table 3. Influence of final temperature Tfinal (HR of 20 ℃.min-1)

T_{final} (℃)	VM_{db}%	A_{db}%	FC_{db}%	HHV (MJ/kg)	Yield (%)	Energy transferred in char (%)
600	7.3	37.8	54.9	19.0	39.5	49.7
750	5.5	38.3	56.2	19.2	38.1	48.4
900	2.9	39.9	57.2	19.3	36.6	46.8

T_{final} has an impact on VM in the char. VM was measured to 7.3% and 2.9% for T_{final} of 600 and 900 ℃, respectively. In contrarily, T_{final} doesn't affect much higher heating value (HHV) of the char. Besides, from the measurement of char yield and HHV, the ratio of energy transferred from the RH to the char have been calculated. It can be seen that about 47% of energy was transferred in the char after pyrolysis at 900 ℃. This value slightly increases at lower T_{final} due to an increase in the char yield.

3.4.2. Influence of heating rate

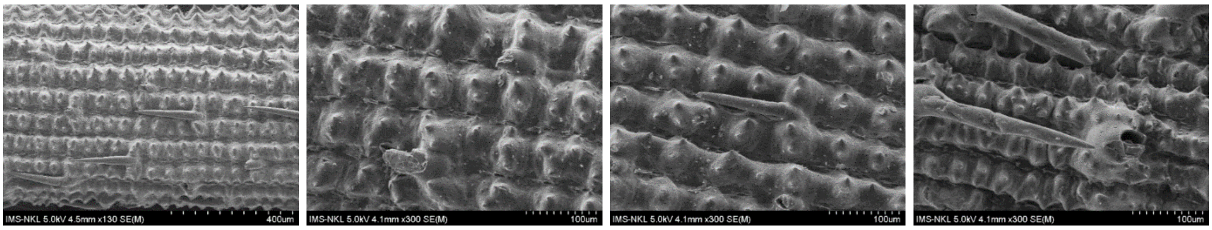
Pyrolysis experiments were performed at HR of 5, 20 and 1800 ℃.min^{-1}. A small change in HR did not impact char yield. In contrarily, when HR is highly increased, the same effect as that of T_{final} was observed. Char yield, HHV, and energy transferred in the char significantly decreases (Table 4).

Table 4. Influence of heating rate (T_{final}: 900 °C)

HR (°C.min^{-1})	VM_{db}%	A_{db}%	FC_{db}%	HHV (MJ/kg)	Yield (%)	Energy transferred in char (%)
5	2.6	39.2	58.2	19.6	36.9	47.9
20	2.9	39.9	57.2	19.5	36.6	47.2
1800	1.9	46.5	51.6	16.3	29.7	32.0

3.4.3. Morphology of RH and RH chars

The SEM of the surface of RH particle and its chars (Figure 5) showed a high degree of roughness. A large number of serrated peaks are placed in lines and parallel to each other. Some pointed thorns are found on the surface and these are easy to be broken by thermal effects. There is no obvious difference between chars produced at different operating conditions. However, the surface of RH char produced at 900°C, 1800°C.min^{-1} seems to be more damaged, expressed through the presence of some cracks and a few small pores. This may presumably due to the sudden change of temperature during pyrolysis.



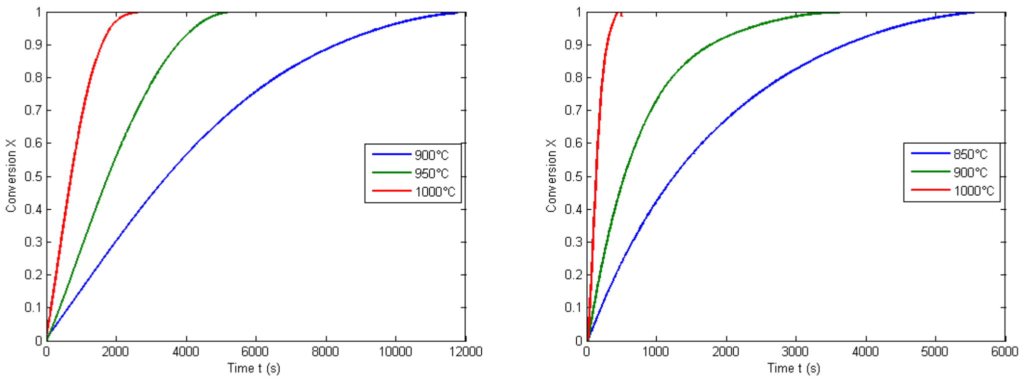
(a) (b) (c) (d)

Figure 5. SEM images of surface of RH and its chars. (a): RH, (b): 600 °C, 20.min^{-1} char, (c): 900 °C, 20.min^{-1} char and (d): 900 °C, 1800 °C.min^{-1} char

3.5. Gasification of RH char particle

3.5.1. Influence of reaction temperature

The influence of temperature on conversion during char-H_2O and char-CO_2 gasification was investigated by varying temperature from 850 to 1000°C (Figure 6) with a partial pressure of 0.2 atm in N_2.



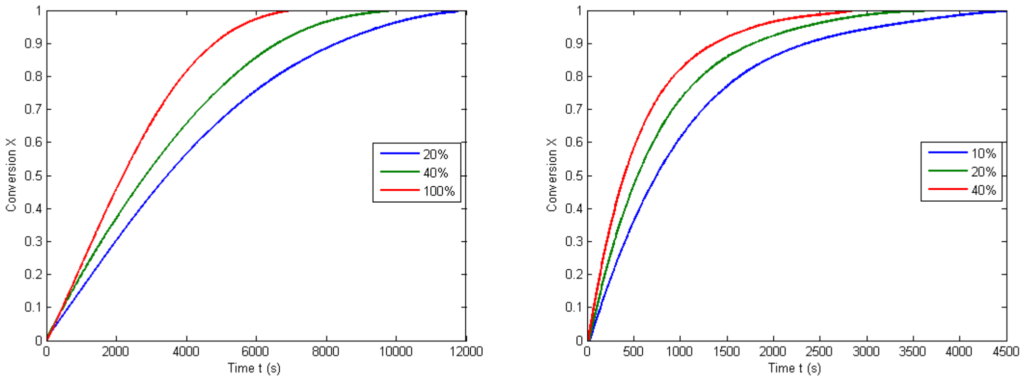
(a) (b)

Figure 6. Influence of reaction temperature on char conversion (a) under CO_2 and (b) under H_2O atmosphere (Partial pressure of the reacting gas: 0.2 atm)

Under CO_2 atmosphere, gasification was completed after 12000, 5000 and 2500s at the temperature of 900, 950 and 1000°C, respectively. Thus, a 100°C increase in gasification temperature increases 4.8 times the reactivity of CO_2 gasification. Under H_2O atmosphere, gasification was completed after 5500, 3500 and 500s at a temperature of 850, 900 and 1000°C, respectively. Thus, a 100°C increase in gasification temperature increases 7 times the reactivity of H_2O gasification. The influence of temperature on CO_2 or steam gasification of RH char is considerably different for the one of wood char. Indeed, a ratio of only 2 to 3 was reported for wood char gasification when increasing the temperature from 900 to 1000°C under the same operating conditions of CO_2 or H_2O [16, 17].

3.5.2. Influence of partial pressure

The influence of partial pressure was studied by varying CO_2 one from 0.2 to 1 atm, and H_2O one from 0.1 to 0.4 at 900°C (Figure 7). An increase in the partial pressure increases the conversion rate of RH char gasification. Under CO_2 atmosphere, gasification was completed after 12000, 10500 and 6500s for the partial pressure of 0.2, 0.4 and 1 atm, respectively. The gasification rate was thus about times faster with 1 atm of CO_2 than with 0.2 atm of CO_2. Under H_2O atmosphere, gasification was completed after 4500, 3500 and 2800s for the partial pressure of 0.1, 0.2 and 0.4 atm, respectively. Gasification was thus about 1.6 times faster with 0.4 atm of H_2O than with 0.1 atm of H_2O.



(a) (b)

Figure 7. Influence of partial pressure of reacting gas on char conversion (a) under CO_2 atmosphere and (b) under H_2O atmosphere (Temperature of reacting gas: 900°C)

Regarding gasifier operating conditions, the impact of partial pressure on kinetics is much lower than that of temperature. Comparing the role of reacting gas nature at 900°C, steam gasification of RH char was about 3.5 times faster than under CO_2 atmosphere. These results are similar compared to wood char where gasification with CO_2 is 2 to 5 times slower than with H_2O under the same conditions [17], [18].

3.5.3. Influence of heating rate

Pyrolysis HR influences the gasification conversion rate of wood char significantly [15]. No effect on RH char conversion has been reported with chars produced at low HR of 5, 10 and 20°C.min^{-1} [5], but this result cannot be extrapolated to high HR. Therefore, in our experiments, we compared the steam gasification conversion rate of chars produced at very different HR: 20 and 1800°C.min^{-1} (Figure 8).
Results showed that a high pyrolysis heating rate accelerates the conversion rate of rice husk char gasification. For a char produced at 20°Cmin^{-1}, gasification was complete after 3500s, whereas for a char produced at 1800°Cmin^{-1}, gasification was complete after 2300s. The gasification rate was thus about 1.4 times faster with a char produced at 1800°Cmin^{-1} than with a char produced at 20°Cmin^{-1}. The effect of heating rate on rice husk char gasification seems to be less important compared to results obtained with wood char gasification, where a much clearer difference in reaction rates was found between chars produced at different heating rates of 2.6°Cmin^{-1}, 12°Cmin^{-1} and 900°Cmin^{-1} [15].

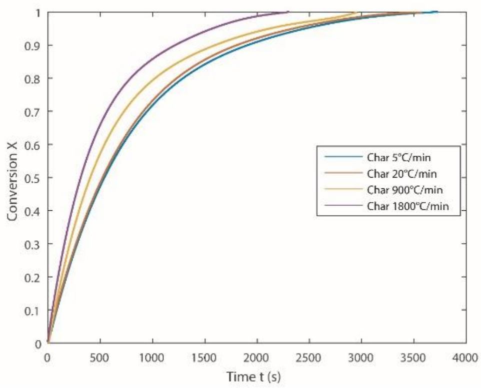


Figure 8. Influence of HR on char conversion (H_2O partial pressure: 0.2 atm, temperature: 900°C)

4. Conclusion

An updated state of the art of RHG technologies was established, from industrial and domestic applications to pilot and laboratory studies. Recent trends and ideas for the development of RH gasifiers at different scales have also been summarised. RH char gasification characteristics at particle scale under CO_2 or H_2O atmosphere were also investigated through a complete parametric study. An increase in T_{final} decreases char yield, remaining VM and energy transferred to the char but does not have much effect on HHV and char morphology. The same effect was shown with a significant increase in HR, except for the fact that we observed small structure damages at the char surface. The temperature was the main factor affecting conversion rate of RH char. An increase from 900 to 1000°C in 0.2 atm accelerates about 4.8 and 7 times the reactivity, under CO_2 or H_2O atmosphere, respectively. A change in the partial pressure of gasification agents has a lesser influence compared to the temperature, but also plays a role in char conversion. The conversion rate decreases in a ratio of about 1.8 when CO_2 partial pressure decreases from 1 to 0.2 atm, and about 1.6 when H_2O partial pressure decreases from 0.4 to 0.1 atm. A significant increase in HR from 20°Cmin^{-1} to 1800°Cmin^{-1} enhanced 1.4 times rice husk gasification kinetics. RHG with H_2O at 900°C, 0.2 atm is about 3.5 times faster than CO_2 atmosphere, which is quite similar to wood gasification. To sum up, this parametric study could provide relevant data to support modelling, design or optimisation of RH gasifier.

5. References

[1] FAO. Rice market monitor. http://www.fao.org/ (2016).
[2] Abdul Salam P, Kumar S, Siriwardhana M. *The status of biomass gasification in Thailand and Cambodia*. Asian institute of technology, 2010.
[3] Nguyen HN, Ha-Duong M, Van de Steene L. A critical look at the rice husk gasification in Cambodia: Technology and Sustainability. *J Sci Technol*; 53.
[4] Zhai M, Xu Y, Guo L, et al. Characteristics of pore structure of rice husk char during high-temperature steam gasification. *Fuel* 2016; 185: 622–629.
[5] Alvarez J, Lopez G, Amutio M, et al. Kinetic Study of Carbon Dioxide Gasification of Rice Husk Fast Pyrolysis Char. *Energy Fuels* 2015; 29: 3198–3207.
[6] Gao X, Zhang Y, Li B, et al. Determination of the intrinsic reactivities for carbon dioxide gasification of rice husk chars through using random pore model. *Bioresour Technol* 2016; 218: 1073–1081.
[7] Bhat A, Ram Bheemarasetti JV, Rajeswara Rao T. Kinetics of rice husk char gasification. *Energy Convers Manag* 2001; 42: 2061–2069.
[8] Nsamba HK, Hale SE, Cornelissen G, et al. Improved Gasification of Rice Husks for Optimized Biochar Production in a Top Lit Updraft Gasifier. *J Sustain Bioenergy Syst* 2014; 04: 225.
[9] Htut Y, Win MM, Myat Khine M. Experimental Investigation of the Pilot Scale Downdraft Gasifier. *IJRCMCE* 2015; 2: 13–18.

[10] Karmakar M, Mandal J, Haldar S, et al. Investigation of fuel gas generation in a pilot scale fluidized bed autothermal gasifier using rice husk. *Fuel* 2013; 111: 584–591.
[11] Ma Z, Zhang Y, Zhang Q, et al. Design and experimental study of a two-stage pilot scale biomass fixed bed gasifier. In: *2013 International Conference on Materials for Renewable Energy and Environment*. 2013, pp. 287–290.
[12] Jairo Ramírez Behainne J, Martínez J. Performance analysis of an air-blown pilot fluidized bed gasifier for rice husk. *Energy Sustain Dev*; 18. Epub ahead of print 1 January 2013. DOI: 10.1016/j.esd.2013.11.008.
[13] Ma Z, Zhang Y, Zhang Q, et al. Design and experimental investigation of a 190 kWe biomass fixed bed gasification and polygeneration pilot plant using a double air stage downdraft approach. *Energy* 2012; 46: 140–147.
[14] Di Blasi C. Combustion and gasification rates of lignocellulosic chars. *Prog Energy Combust Sci* 2009; 35: 121–140.
[15] Mermoud F, Salvador S, Van de Steene L, et al. Influence of the pyrolysis heating rate on the steam gasification rate of large wood char particles. *Fuel* 2006; 85: 1473–1482.
[16] Mermoud F, Golfier F, Salvador S, et al. Experimental and numerical study of steam gasification of a single charcoal particle. *Combust Flame* 2006; 145: 59–79.
[17] Van de steene L, Tagutchou JP, Escudero Sanz FJ, et al. Gasification of woodchip particles: Experimental and numerical study of char–H2O, char–CO2, and char–O2 reactions. *Chem Eng Sci* 2011; 66: 4499–4509.
[18] Harris DJ, Smith IW. Intrinsic reactivity of petroleum coke and brown coal char to carbon dioxide, steam and oxygen. *Symp Int Combust* 1991; 23: 1185–1190.