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ORIGINAL PAPER

# Comparison of Kinetic Models for Carbon Dioxide and Steam Gasification of Rice Husk Char

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**Abstract** This study reports carbon conversion rate calculated from the online gas analysis obtained from rice husks char gasification by using carbon dioxide and steam as reactive gases. Rice husks char is produced by the pyrolysis of rice husks in a muffle furnace at 450 °C during 45 min. The gasification tests are carried out at several temperatures 900, 950 and 1000 °C by using carbon dioxide and steam under isothermal conditions. The volume reaction model (VRM), shrinking core model (SCM) and random pore model (RPM) are studied to interpret obtained experimental data. Kinetic parameters such as activation energy (E) and pre-exponential factors (A) are determined from gas-analysis data by using Arrhenius equation. From results confrontation, between experimental data and obtained results from used models, it is found that RPM agrees better with experimental data than the other two models. We also obtained an activation energy of 165.8 kJ/mol and pre-exponential factor of 2595.4 $s^{-1}$ for $\Psi$ equal to 3.8 for carbon dioxide gasification and, respectively, 152.9 kJ/mol and 3473.4 $s^{-1}$ from $\Psi = 2.16$ for steam gasification.

**Keywords** Conversion rate char · Kinetics · Model · Reactivity · Biomass

## Introduction

Nowadays, renewable energies take a very important place in nation's development strategies. Among renewable energies resources, we distinguish biomass energy. This study reports the work done on energy recovery from agricultural residues such as biomass by using thermochemical conversion through gasification.

Thermochemical conversion of biomass offers potentiality for the transition from a fossil-fuel-driven global economy. Pyrolysis and gasification have been identified as the most favourable thermochemical processes for biomass's conversion for renewable energy exploitation due to their low sulphur and nitrogen contents. Biomass gasification products contain hydrogen, methane, carbon monoxide… etc. They can be used as fuel in a gas turbine to generate electricity in rural areas [1]. In this context, pyro-gasification of this biomass is able to produce power by using mixture gas resulting from the pyro-gasification reaction.

The economy of many african countries is based on agriculture. This makes Africa have a great agricultural potential. This agricultural production generates waste which must be developed. According to the USDA, rice production in the world for the agricultural campaign 2010/2011 had reached figure record of 459.7 million tons (4% more than agricultural campaign 2009/2010) and reached a threshold of 479.2 Mt in 2014 [2]. Indeed, it is shown that sub-Saharan Africa produces enough cereals without forgetting cotton. According to FAO statistics in 2006 [3], average growth rates of sorghum, corn, millet, rice and cotton in West Africa were respectively 1.4, 2.9, 3.5, 1.8 and 4.8%. Thus, cotton, millet, corn and rice come ahead of productions. However, in terms of biomass, we have rice husks knowing that sheets, stems, straws and sounds of rice are very often used in rural area to feed animals or to fight against ground erosion, and

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for other useful activities of the rural living. The Republic of Benin shows a considerable production rate of rice husks in the rice mills with a growth rate in production of rice in full evolution these last year's [4]. Benin generates at average 160,503 tons of rice husks per year from rice mills, according to crop years' from 2004/2005 to 2013/2014. Benin is characterized by a very weak rate of electrification in rural area [5]. Consequently, this increased the interest in the usage of rice husks as a renewable source of energy [6, 7]. Converting rice husks into gaseous is beneficial to countries which have no conventional energy resources and of which economies are tied to agriculture and local industries like Benin. In this context, the pyro-gasification of this biomass could be a solution for power production. Kinetic parameters information are of particular importance for selection of gasification conditions as well as the logical design of a reactor for the subsequent char gasification by using carbon dioxide and/or steam. This work, carried out using an instrumented installation equipped with a fixed bed reactor, presents a method for predicting the reactivity of biomass char as a function of temperature and conversion time by online products chromatography analysis.

Several authors have worked on gasification with carbon dioxide by using several kinetic models: Tangsathitkulchai et al. [8] conducted a comparison of kinetic models (VRM, SCM, RPM and MVRM: Modified Volume-Reaction Model) during gasification of coconut-shell char from TGA method by using carbon dioxide. Similarly, they proceeded to the determination of kinetic parameters from experimental data of the rice husks gasification reaction, which are interpreted as based on VRM and SCM [9]. Modelling biomass char gasification kinetic in a fluidized bed reactor with steam and carbon dioxide, Kramb et al. [10] used uniform conversion model (UCM), random pore model (RPM), modified random pore model (MRPM), hybrid random pore model (HRPM), hybrid modified random pore model (HMRPM) and the proposed one in their own work. Four types of char were tested for gasification with $CO_2$ by using a pressured drop tube furnace or thermo gravimetric analysis at high temperature and pressure [11]. They also applied the n$^{th}$ order equations rate and the Langmuir–Hinshelwood model to char gasification reaction with RPM. $CO_2$ gasification kinetics of olive residue has been studied by using the VRM and the Langmuir–Hinshelwood model [12].

Several authors worked on gasification of rice husk [9, 13, 14]. Most authors put more emphasis on the effluence of pyrolysis temperature on the char reactivity during gasification and were limited to 900 °C. They also studied the reactivity of char with carbon dioxide. The SCM model controlled by the chemical regime simulates better the kinetics of rice husk for temperatures below 850 °C and beyond this temperature and precisely for temperatures above 900 °C, the SCM model under control of gas diffusion in the gaseous film would better simulate the kinetics of rice husk [9], while other authors [13, 15] have proved that RPM model would be more indicated beyond 850 °C and obtain relatively high values of the structural parameter (Ψ 3.5–6). All these authors studied the reactivity of rice husk char prepared either by flash pyrolysis or at high temperatures (600–800 °C). In this work we studied the reactivity of rice husk char with two reactive gases and for temperatures higher than 900 °C from rice husk char prepared by pyrolysis of rice husk at 450 °C during 45 min, using a muffle furnace. The objective of this study is to find the model that better simulates the rice husk char gasification from existing models (VRM, SCM and RPM) with experimental data. Specific objectives are to determine the apparent kinetic parameters during the gasification reaction with carbon dioxide on the one hand and steam on the other hand, then to predict the conversion rate of rice husk char and finally to study the kinetic ratio between the two reactions (Boudouard reaction and steam gasification).

## Materials and Methods

### Raw Material Characterization

The rice husks used for this study come from Benin (West Africa). The physicochemical properties of the raw rice husk and rice husk char, obtained by pyrolysis, are gathered in Table 1. The determination of the ash content was carried out according to NF M 03–003. The volatile matter index was obtained by using the thermo gravimetric analysis apparatus with a heating rate of 5 °C/min under inert atmosphere of helium with a gas output of 12 NL/h. Determination of the fixed carbon ratio was carried out according to NF M 03–006. The ultimate analysis was

**Table 1** Determined characteristics for rice husk sample and rice husk char

| Performed analyzes | Rice husks sample | | Rice husks char |
|---|---|---|---|
| | Components | Values (%) | |
| Proximate analysis | Moisture content | 7 | – |
| | Ash content | 18.31 | 44.9 |
| | Volatile matters | 70.6 | 14 |
| | Fixed carbon | 11.9 | 41.8 |
| Ultimate analysis | C | 39.9 | 44.3 |
| | H | 4.77 | 2.11 |
| | O | 35 | 8.2 |
| | N | 0.41 | 0.53 |
| Physicochemical analysis | Cellulose | 48.9 | |
| | Hemicellulose | 18.4 | |
| | Lignin | 14.8 | |

carried out according to the NF EN 15104, while biomass physicochemical analysis is made according to the Van Soest proportioning method.

The pyrolysis reactions were performed in a muffle furnace. Crucibles with vacuum lids were weighed with and without samples. At a heating rate set at 10 °C/min, the furnace is brought to the pyrolysis temperature of $T_c = 450$ °C from the ambient temperature of 25 °C. Once $T_c$ is reached, the crucible with sample (dry rice husk char) is placed inside for 45 min. At the exit of the furnace, the assembly is immersed in an atmosphere of less than 0 °C in order to avoid possible reactions inside the crucible. Several pyrolysis tests have been carried out in order to constitute a homogeneous and representative mixture of the rice husk char.

### Experimental Apparatus and Procedures

Gasification tests were carried out by using an instrumented installation equipped with a fixed bed reactor and chromatography gas analyzer, showed in Fig. 1.

With this installation, it became possible to investigate reaction kinetic of rice husk char gasification, by following the variation of carbon conversion during its reaction with $CO_2$ or steam, versus time, by gasification products analysis.

In this context, and in order to ensure temperature uniformity and avoid preferential flows in reacting bed, rice husk char (10% wt) is mixed with sand (90% wt), having a mean diameter of the order of 300 μm, in a cylindrical sample holder (provided with a sintered refractory steel at its lower end).This assembly is placed in a vertical tubular reactor equipped with a heating element, in order to ensure reactor's internal temperature. A temperature controller, made of thermocouple (and a sensor), placed in the middle of sample bed, is used to measure and control reactor's internal temperature. It is surmounted by a gas supply circuit. The amount of reactive and/or inert gas ($N_2$ or $CO_2$ or steam) supplies the reactor. The water supply is provided and regulated by means of a volumetric pump, Waters 510, which transfers water (in liquid form) to a zone of gas preheating where it instantaneously vaporized. The reactive gas ($N_2$ or $CO_2$ or steam) passes through a preheating zone at a temperature of 300 °C before reaching char/sand mixture bed inside the reactor.

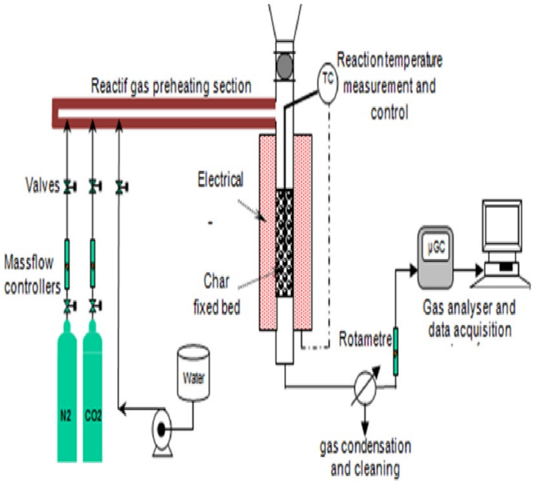

**Fig. 1** Diagram of the used experimental installation for gasification reactions of fixed bed type

The reactive bed is preheated to the desired temperature under inert atmosphere of nitrogen $N_2$ at flow rate of 10 NL/h. The reactive gas flow rate is fixed to 40 NL/h for carbon dioxide and 1.5 ml/min for liquid water. During the gasification reactions, the nitrogen $N_2$ flow rate is reduced to 4 NL/h in the reactor and serves as a reference to calculate the amount of non-condensable gases produced during the experiment. Meanwhile, the reactive gas is supplied to the bed. This gas contains a mixture of 4 NL/h of nitrogen and 40 NL/h of reactive gas. The produced gases pass through a gas condensation and filtration system before gas analysis.

Micro gas chromatography (GC) analyser is used to analyse, online, the composition of non-condensable gas fractions obtained from the gasification tests. The tests are carried out on rice husk char, by using carbon dioxide and steam as reactive gases, at three temperatures: 900, 950 and 1000 °C. The analysis of the gases at the outlet of the fixed bed reactor is carried out on dry matter. The gases analysed during a regular period of 180 s (3 min) allow us to calculate the mass of converted carbon as a function of time, after a mass balance calculation. The gases analysed are carbon monoxide (CO), carbon dioxide ($CO_2$), hydrogen ($H_2$), methane ($CH_4$) and nitrogen ($N_2$).

## Results and Discussion

The kinetic model of rice husks char gasification reaction are performed by studying three different models (VRM, SCM and RPM) from the obtained experimental data by using the described installation.

### Experimental Results

Using the composition of product gasification and the amount of $N_2$ used as reference gas, the carbon conversion rate during the reaction, at a given time (t), can be calculated from a carbon mass balance. The carbon conversion rate is then defined by following the equation [16]:

$$X = \frac{m_{c-converted}}{m_c} \tag{1}$$

$m_{c-converted}$ and $m_c$ are respectively the mass of carbon converted and the initial mass of carbon (at the beginning of the gasification reaction).

The carbon conversion rate calculated (X) in this study doesn't take into account certain hydrocarbon trapped in the condensation section or certain hydrocarbon which are not measured by micro-GC chromatography as tar.

From the formula (1) we plot conversion rate of rice husk char as a function of time, according to each reactive gas. In Figs. 2 and 3 are showed the experimental variation of conversion rate versus time, obtained from rice husk char gasification for temperatures: 900, 950 and 1000 °C respectively with carbon dioxide and steam. From these results, one can observe a significant gap in the conversion rate, as a function of time, from the temperature of 900–950 °C. Note that, the temperature exerts a considerable influence on the kinetics of gasification reactions, according to Arrhenius law. Moors observed the overlapping of the curves at high temperatures when they were studying the effect of temperature on the gasification of bituminous char in a WMR at 1.5 MPa under 2.5% $CO_2$ gas stream [17]. Conversion rate of rice husk char is very slow (4000–1000 s). Everson et al. [18] varied the reaction temperature from 850 to 900 °C and observed that, at lower reaction temperature, the reaction completion requires longer reaction time. The similar results are obtained when Tang et al. [19] observed the same overlapping phenomenon when they were studying the gasification of low melting char at high temperature.

## Effects of the Reactive Gases

In order to study and compare the effects of the reactive gases on the conversion rate, the results giving the conversion rates that were obtained with the two reactive gases (carbon dioxide and steam) at the two extreme temperatures (900 and 1000 °C) are presented in Fig. 4. The carbon conversion rate with steam is greater than the one obtained with carbon dioxide. Indeed, it is noticed that the sample mass loss under $CO_2$ atmosphere is very small while at the same temperature, the reaction rate with steam is appreciable. This result is in accordance with the studies on wood char gasification with $CO_2$ and steam, which shows that the reaction rate of carbon with steam is 1.5 faster than Boudouard reaction [20].

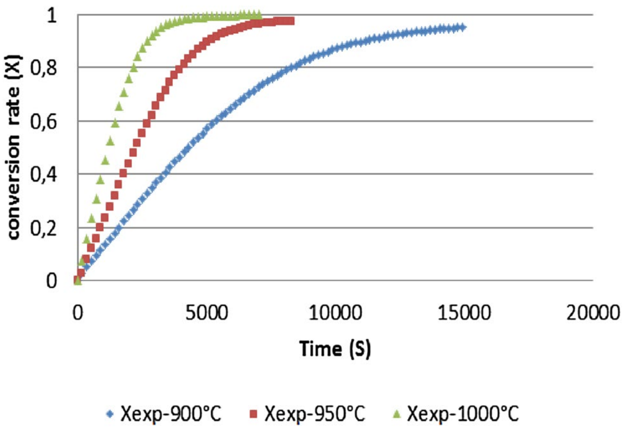

**Fig. 2** Plot of X versus time at 900, 950 and 1000 °C from carbon dioxide

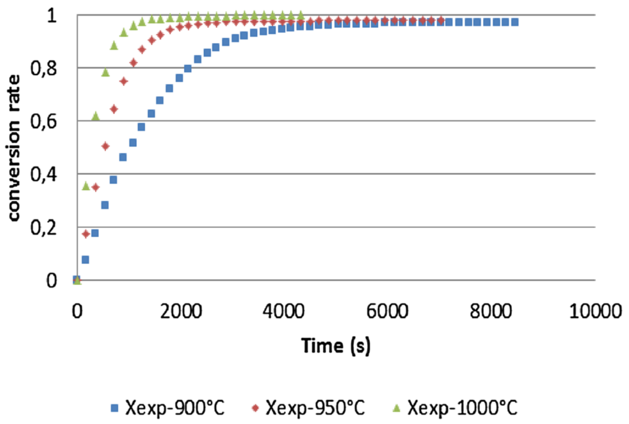

**Fig. 3** Plot of X versus time at 900, 950 and 1000 °C from steam

## Determination of Kinetic Parameters

To determine the kinetic parameters, three models are studied in order to find which one simulates better the experimental results by giving the kinetics of the rice husks char of gasification reactions. The rate of conversion is expressed as:

$$\frac{dx}{dt} = kf(x) \tag{2}$$

where k is the reaction rate constant, which is based on gas temperature and the partial pressure of reactive gas, f(x) is the term which expresses the reactivity dependence on conversion and can take a number of different forms [21]. Assuming that the concentration of carbon dioxide remains

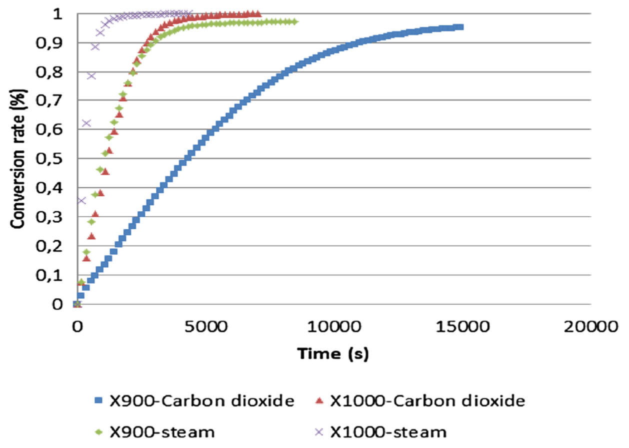

**Fig. 4** Reactive gas effect on the conversion rate versus time for 900 and 1000 °C

constant during the test, the reaction rate of gasification can be represented by means of Arrhenius equation as:

$$k = Ae^{\frac{-E}{RT}} \tag{3}$$

where A, E and R are respectively, the pre-exponential factor, activation energy and universal gas constant.

Three models are applied to study the reactivity of rice husk char knowing the conversion rate (X):

- VRM (volume reaction model) [22]. It assumes a homogeneous reaction throughout a char particle and the reaction rate and is described as follows [23]:

$$\frac{dx}{dt} = k_{VRM}(1 - X) \tag{4}$$

- SCM (shrinking core model). It assumes that the reaction initially occurs at the external surface of char and gradually moves inside. At the intermediate conversion of the solid, there is a shrinking core of non-reacted solid and its reaction rate is given by [24]:

$$\frac{dx}{dt} = k_{SCM}(1 - X)^{2/3} \tag{5}$$

- RPM (random pore model): It considers the overlapping of pore surfaces which reduces the area that is available for reaction [25]. It can predict the maximum value of the reactivity as the reaction proceeds because it simultaneously considers the effects of pore growth during the initial stages of gasification and the destruction of pores due to the coalescence of adjacent pores. The reaction kinetic is described as follows:

$$\frac{dx}{dt} = k_{RPM}(1 - X)\sqrt{[1 - \Psi \ln(1 - X)]} \tag{6}$$

$$\Psi = \frac{4\pi L_0(1 - \varepsilon_0)}{S_0^2} \tag{7}$$

$L_0$ , $\varepsilon_0$, $S_0$ are respectively the pore length, the solid porosity and the surface area that are related to the pore structure of the non-reacted sample.

Its value is experimentally obtained. Seo et al. [22] have to estimate the value of $\Psi$ according to the formula (8). $x_{max}$ is determined from experimental data and represents the peak of parabolic curve-fits giving dx/dt versus x.

$$\Psi = \frac{2}{\left[2\ln\left(1 - x_{max}\right) + 1\right]} \tag{8}$$

First, the kinetic constant is determined by plotting $(2/\Psi) \times \left[\sqrt{1 - \Psi ln(1 - \mathrm{X})} - 1\right]$ versus time for each temperature. The structural parameter $\Psi$ is evaluated from formula (8) below, which requires the knowledge of $x_{max}$.

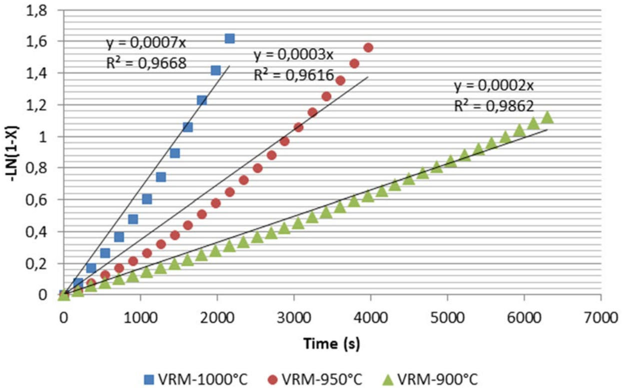

**Fig. 5** Plots of linearized VRM during $CO_2$

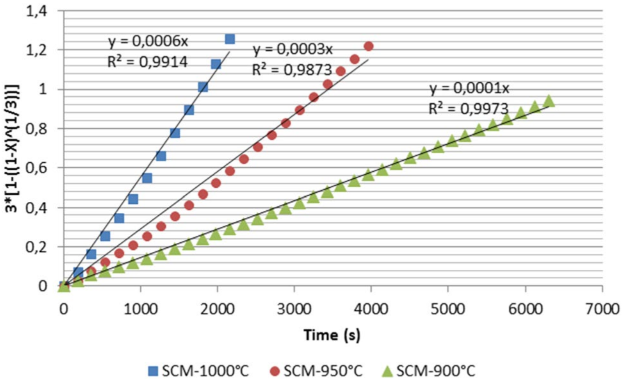

**Fig. 6** Plots of linearized SCM during $CO_2$

Then, to determine $x_{max}$, we wrote in MATLAB 7.0 a program that outputs the maximum value of x from two columns issued in Excel containing respectively the conversion rate (X) and the reaction rate (dX/dt) for each temperature. Finally, from the three values of $\Psi$ found (900, 950 and 1000 °C), we determined the average, which allows us to predict, from the determined kinetic parameters, the conversion rate of rice husk char whatever the reaction temperature is. Figures 5, 6, 7, 8, 9 and 10 show application of the three different models for the experimental data from gasification with carbon dioxide and steam. The constants of the reaction of the three different models are obtained from the slope of each of the graphs depending on either carbon dioxide or steam gasification. As different curves show it, we observe more dispersion of points for VRM model, much less for SCM model and better linearity for RPM model.

The $\Psi$ values obtained in this study for rice husks char gasification with carbon dioxide and steam are respectively 3.8 and 2.16. These found values of $\Psi$ for RPM model agrees well with the set conditions by using the RPM model [26]. In this study, the maximum value of conversion rate ($X_m$),

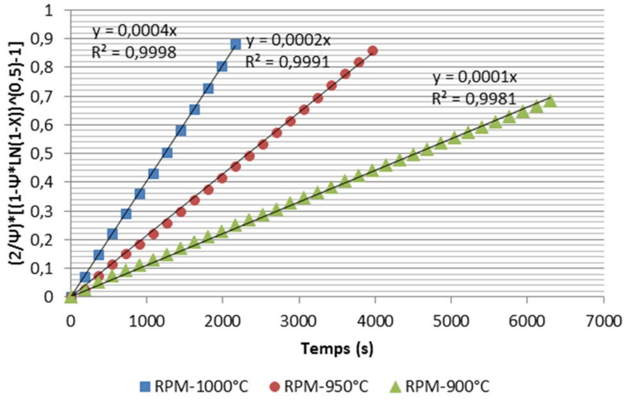

Fig. 7 Plots of linearized RPM during $CO_2$

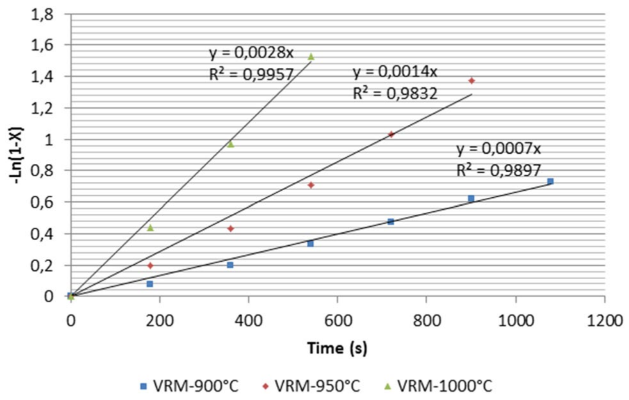

Fig. 8 Plots of linearized VRM during water steam

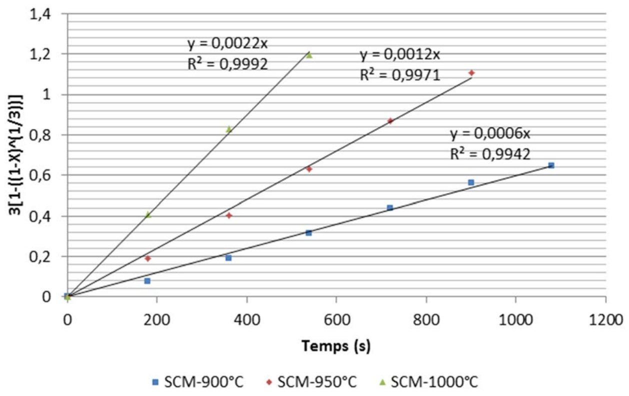

Fig. 9 Plots of linearized SCM during water steam

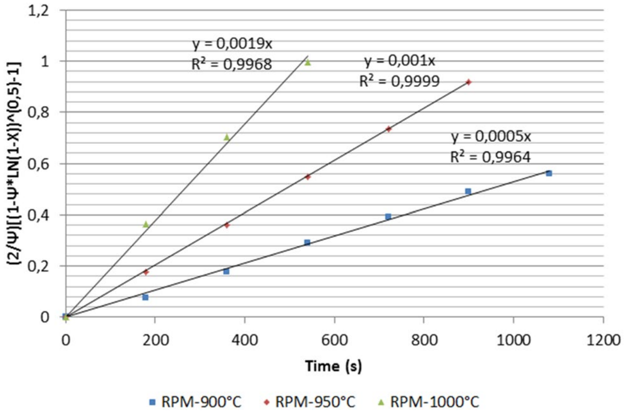

Fig. 10 Plots of linearized RPM during water steam

according to Zhang et al. [26], is 0.21 for gasification with carbon dioxide and 0.036 for gasification with steam. These values are well below of 0.393 found in their work through application of the following formula:

$$X_m = 1 - e^{\frac{2-\Psi}{2\times\Psi}} \quad (9)$$

For each model, kinetic parameters were determined with the corresponding standard deviations and summarized in Table 2.

In general, the value of the structural parameter is influenced by experimental gasification conditions (partial pressure of the gas and reaction temperature) on the one hand, and strongly influenced by the pyrolysis temperature on the other hand [14]. Indeed, the higher the pyrolysis temperature is, the higher the value of the structural parameter Ψ is [27]. If the value of Ψ (3.16) found in this study is close to that found by Gao et al. [15] who have obtained (Ψ 3.5–6) and Alvarez et al. [13] who have obtained (3.54) from the rice husk char, this value is similar to those obtained by Gil et al. [28] who obtained (Ψ 2.9–3.6) from plastic waste char. However, Tangsathitkulchai et al. [8] obtained (Ψ 16.9–45.6) from coconut char which deviates of those obtained in this study. Furthermore, Xu et al. [29] obtained very low values of Ψ (0.0003–1.13) and showed the influence of the chemical composition of the ash (ionic metals) on the improvement of the reaction rate. The reaction bed as described in the present study is porous in addition to the rice husk char density in the fine sand. The low recorded values of the structural parameter Ψ in this study may be due to a very limited development of the pore during the reaction [13]. According to the Boudouard reaction and steam gasification, we obtain respectively 165.8 and 152.9 KJ/mol by considering a reaction order equal to 1 with the hypothesis that the partial pressure of the reactive gas is constant. Bhat et al. [9] obtained respectively 200 KJ/mol (with rice husk char) and 180 KJ/mol (with powder of rice husk char) with water steam and carbon dioxide from VRM and SCM respectively. However, the activation energies obtained in the present study are lower than those found by Gao et al. [15] (230 KJ/mol) and by Alvarez et al. [13] (266.8 KJ/mol) with carbon dioxide for the reaction order different from 1. The difference between the activation energies can be due both to ash content in the rice husk char which is 44.9% in this study versus 6.3% in studies of Alvarez et al. [13] and to the chemical composition of the ash ($K_2O$, $Na_2O$, CaO, MgO and $Fe_2O_3$) according to Ollero et al. [12] without forgetting the pyrolysis temperature which has an effect on the nature and the reactivity of the rice husk char [27].

### Comparative Study of the Conversion Rates

The accuracy of a prediction model can be assessed by computing its Estimated Standard Error (ESE) labelled $\sigma_{CSt}$ and defined according to the following equation [30]:

$$\sigma_{CSt} = \sqrt{\frac{\sum_{i=1}^{N}\left[\frac{X_{pred}-X_{exp}}{X_{pred}}\right]^2}{N-2}} \tag{10}$$

$X_{pred}$ and $X_{exp}$ are respectively the predicted model and experimental char conversion rates, and N is the number of data points of conversion (X)–(t) time (t) data. Table 3 shows the comparison of the ESE values of the two studied kinetic models (SCM and RPM) respectively obtained with carbon dioxide and steam gasification.

Based on regression coefficients values ($R^2$) (Figs. 5, 6, 7, 8, 9, 10) and ESE (Table 3), and also date dispersion data in function of time, it is noted that kinetics' experimental data for rice husks char gasification, respectively with carbon dioxide and steam, are best described by RPM when the temperature is higher than 900 °C. The recorded trend, for the predictive capability of the tested models, is an increasing order corresponding to that following: VRM < SCM < RPM.

For temperatures higher or equal to 900 °C, the kinetic constant of steam reaction is 1.4 times greater than that of Boudouard reaction. Thus, the apparent kinetic parameters are determined by RPM model which fits better the experimental data:

- According to Boudouard reaction: E = 165.8 kJ/mol and A = 2595.4 $S^{-1}$
- According to steam gasification: E = 152.9 kJ/mol and A = 3473.4 $S^{-1}$

With these obtained kinetic parameters, we can now have access to a model based on RPM model which allows us to simulate kinetics reactions of rice husk char during gasification. A comparative study is also carried out between the experimental conversion rates and the one obtained directly from the RPM model as showed in Figs. 11 and 12.

RPM model simulates very well the rice husk char reaction with carbon dioxide up to a conversion rate of 80% at T = 900 °C and above 90% for a temperature greater than 950 °C. However, this rate of conversion is 60% at T = 900 °C and reached 90% for a temperature greater than 950 °C for its reaction with steam even if it's noted that the temperature plays an important role in the chemical reaction and on the diffusion gas. In fact, after 6000 s reaction time, 66% of the rice husk char is converted at 900 °C whereas complete conversion at the same time has reached 1000 °C with carbon dioxide. We clearly observe reactivity amelioration with increasing temperature as was observed also by Gomez-Barea et al. [31] for wood char gasification.

**Table 2** Obtained kinetics' parameters using the three tested models: VRM, SCM and RPM: gasification with $CO_2$ and gasification with water steam

Gasification with $CO_2$

| T (°C) | $K_{VRM}$ | $R^2$ | $K_{SCM}$ | $R^2$ | $K_{RPM}$ | $R^2$ |
|---|---|---|---|---|---|---|
| 900 | $1.77 \times 10^{-4}$ | 0.9862 | $1.49 \times 10^{-4}$ | 0.9973 | $1.06 \times 10^{-4}$ | 0.9981 |
| 950 | $3.94 \times 10^{-4}$ | 0.9616 | $3.13 \times 10^{-4}$ | 0.9873 | $2.17 \times 10^{-4}$ | 0.9991 |
| 1000 | $4.45 \times 10^{-4}$ | 0.96688 | $5.85 \times 10^{-4}$ | 0.9914 | $4.06 \times 10^{-4}$ | 0.9998 |

| (E, A) | E (KJ/mol) | A ($S^{-1}$) | $R^2$ | E (KJ/mol) | A ($S^{-1}$) | $R^2$ | E (KJ/mol) | A ($S^{-1}$) | $R^2$ | Ψ |
|---|---|---|---|---|---|---|---|---|---|---|
| Values | 178.14 | 15450.5 | 0.9984 | 169.63 | 5395.3 | 0.9994 | 165.806 | 2595.4 | 0.9998 | 3.18 |

Gasification with water steam

| T (°C) | $K_{VRM}$ | $R^2$ | $K_{SCM}$ | $R^2$ | $K_{RPM}$ | $R^2$ |
|---|---|---|---|---|---|---|
| 900 | $7.02 \times 10^{-4}$ | 0.9897 | $6.24 \times 10^{-4}$ | 0.9942 | $5.4 \times 10^{-4}$ | 0.9964 |
| 950 | $15.3 \times 10^{-4}$ | 0.9832 | $12.4 \times 10^{-4}$ | 0.9971 | $10.3 \times 10^{-4}$ | 0.9999 |
| 1000 | $28.4 \times 10^{-4}$ | 0.9957 | $22.3 \times 10^{-4}$ | 0.9992 | $18.4 \times 10^{-4}$ | 0.9968 |

| (E, A) | E (KJ/mol) | A ($S^{-1}$) | $R^2$ | E (KJ/mol) | A ($S^{-1}$) | $R^2$ | E (KJ/mol) | A ($S^{-1}$) | $R^2$ | Ψ |
|---|---|---|---|---|---|---|---|---|---|---|
| Values | 173.9 | 39576.8 | 0.9981 | 158.16 | 6935.4 | 0.9996 | 152.92 | 3473.4 | 1 | 2.16 |

**Table 3** Estimated standard error (ESE) for testing the accuracy of kinetic model prediction for $CO_2$ and water steam gasification

| Gasification temperature (°C) | Data number (N) | Estimated standard Error with $CO_2$ | | |
|---|---|---|---|---|
| | | RPM | SCM | VRM |
| 900 | 84 | 0.083 | 0.046 | 0.134 |
| 950 | 47 | 0.046 | 0.11 | 0.198 |
| 1000 | 40 | 0.009 | 0.07 | 0.183 |
| Gasification temperature (°C) | Data number (N) | Estimated standard Error water steam | | |
| | | RPM | SCM | VRM |
| 900 | 48 | 0.053 | 0.123 | 0.068 |
| 950 | 40 | 0.025 | 0.446 | 0.052 |
| 1000 | 25 | 0.024 | 0.531 | 0.029 |

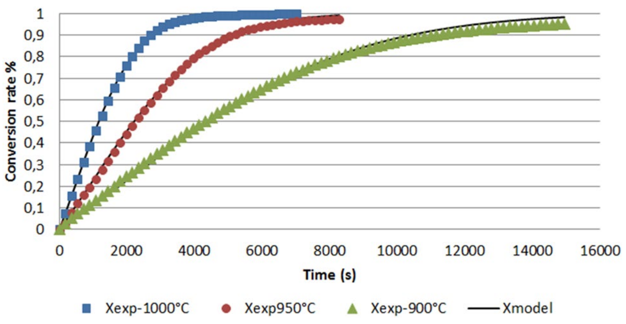

**Fig. 11** Comparative study of experimental conversion rate to that achieved by RPM at cited temperatures in the legend using carbon dioxide

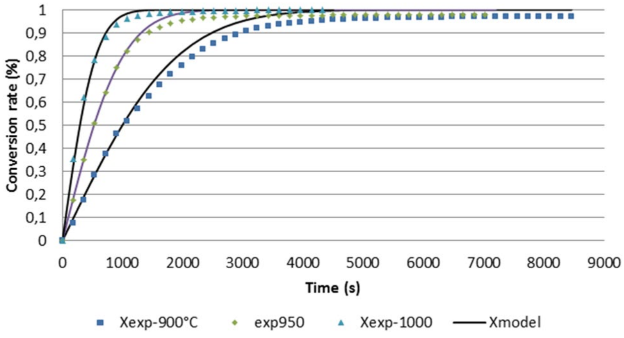

**Fig. 12** Comparative study of experimental conversion rate to that achieved by RPM at cited temperatures in legend using water steam

## Conclusion

A set of tests on kinetic models are carried out to find the one that best simulates the gasification reactions of rice husk char under carbon dioxide and steam atmospheres respectively. It is shown that the RPM model gives a better prediction of experimental data. The increase in temperature causes an increase in reaction's rate more sensitive from 900 to 950 °C. The reaction is subjected to a double control: chemical reaction and internal distribution.

Using the RPM model, different kinetics' parameters have been calculated for each of the rice husks char gasification and validated respectively for $\Psi = 3.8$ under carbon dioxide atmosphere and $\Psi = 2.16$ under steam atmosphere from rice husk char, obtained from the pyrolysis of rice husk in a muffle furnace at 450 °C during 45 min.

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