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Professor Stan Kolaczowski 10 Dec 2015

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1 **Steam gasification of a refuse derived char: Reactivity and kinetics**

2

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7

8 **Abstract**

9 A char was obtained from a commercial pilot-scale gasifier, which had been operating
10 with a refuse derived fuel (RDF). Using this char, steam gasification experiments were
11 then performed in a 15.6 mm i.d. packed bed tubular reactor. The effect of reaction
12 temperature was studied (800 °C to 900 °C), and also the partial pressure of steam were
13 in the range 33.3 kPa to 66.7 kPa. With the aid of the Shrinking-Core and the Uniform-
14 Reaction models, kinetic parameters were estimated (apparent activation energy varied
15 from 96 kJ mol⁻¹ to 162 kJ mol⁻¹). It was also found that at lower carbon conversions
16 (e.g. 10 % to 60 %) the RDF-derived char appeared to be more reactive than other bio-
17 chars reported in the literature. However, at higher conversions (> 60 %), its apparent
18 reactivity decreased with carbon conversion, thereby behaving in a similar manner to
19 chars derived from coal.

20

21 **Key words:** Kinetic, steam gasification, RDF-derived char, biomass.

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24 **1. Introduction**

25

26 There is much interest in the development of processes in which biomass (e.g.
27 wood) and refuse derived fuels (RDFs) may be converted into a gaseous stream, which
28 could then be used as a fuel to produce energy, or act as a chemical intermediate. Based
29 on information in the literature, it is well recognized that when biomass is gasified in the
30 presence of air, then a gas mixture of CO, H₂, CO₂, N₂ and H₂O is produced, and a char
31 stream is also produced as a by-product [1, 2, 3, 4]. In such processes, the char arises
32 from the nature of the gasification process, where some of the carbon in the feedstock
33 remains, combined with the residual ash, which needs to be removed from the process.
34 As such biomass gasification processes are being developed, there has been great
35 interest in the conversion of the residual carbon in the char into a gaseous fuel, and such
36 a process could be developed using steam to gasify the char.

37

38 *1.1. Motivation for the gasification of RDF derived char*

39

40 In their discussions with a number of different companies that were developing
41 such biomass to energy processes, the authors of this paper were made aware of the
42 importance that such companies placed on the need to find economically viable ways of

List of Abbreviations

AAEM	Alkali and Alkaline Earth Metallic
QMS	Quadrupole Mass Spectrometer
RDF	Refuse Derived Fuel
TGA	Thermo Gravimetric Apparatus

43 converting the carbon in the char into a useful form of gaseous fuel. Otherwise, the char
44 produced had to be disposed of off-site, which created a disposal cost and a loss in
45 revenue from the potential of converting the carbon in the char into gaseous fuel. These
46 considerations led to the work described in this study. In such processes, there is
47 thermal energy available, which could be used to produce steam on-site. So using steam
48 in such a process makes sense.

49 Although there have been many kinetic studies performed on the steam
50 gasification of char [5, 6, 7], these in general have been performed on char from wood,
51 food waste, and coal. There is relatively little data on the gasification of char produced
52 from a process using a refuse derived fuel (RDF). However, it is well recognized that
53 char reactivity depends not only on operating parameters (e.g. temperature, pressure,
54 steam ratio), but also on the source of the char and how it was produced. For example,
55 wood char reactivity is reported to increase with carbon conversion [8], whereas that of
56 coal char decreases with carbon conversion [9]. The presence of inorganic elements in
57 the char may also have a favourable catalytic effect, e.g. [1]

58

59 ***1.2. Effect of temperature***

60

61 Many of the studies in the literature on the steam gasification kinetics of chars
62 are performed at temperatures in the region of 700 °C to 1000 °C, reflecting the
63 temperature range inside the reaction zone of a gasifier (fluidized/fixed bed), for
64 example, in:

65 Pavier *et al.* [10] - char gasification experiments are performed with steam at 850
66 °C, 900 °C, 950 °C and 1000 °C.

67 Khor *et al.* [11] - charcoal gasification experiments are performed with steam and
68 air at 800 °C to 950 °C in the bed.

69 Chaudhari *et al.* [3] - steam gasification of chars at 700 °C, 750 °C, and 800 °C.

70 According to Blasi [12], at such high temperatures (<1000 °C), the rate of diffusion
71 through the pores of reacting chars plays no role in determining the overall rate of
72 reaction, so measurements at such high temperatures are considered to be in the
73 kinetically controlled regime. In some of the studies reported in the literature, by
74 making comparisons between the time-scales of the different phenomena involved, a
75 simplified approach to kinetic analysis has been adopted. Such a technique is described
76 in Dupont *et al.* [13], who applied it to a study on the gasification of biomass with
77 steam.

78 Particle size will also have an effect, and this is discussed in Section 1.4.

79

80 ***1.3. Effect of gas velocity***

81

82 The effect of gas velocity was also considered in some studies. For example,
83 Paviet *et al.* [5] reported that gas velocity had influence on the external mass transfer
84 resistance, and at high gas velocity (from 10 cm s⁻¹ to 20 cm s⁻¹) this influence could be
85 considered to be negligible. Mermoud *et al.* [8] also suggested that gas velocity had a
86 gentle influence on gasification.

87

88 ***1.4. Effect of particle size***

89

90 Char particle size was reported to have no effect by some authors (e.g. Paviet *et*
91 *al.* [5]), while others (e.g. Mermoud *et al.* [8]; Mani *et al.* [14]) have reported that as the
92 particle size is increased, then this has a retarding effect on the rate.

93 Paviet *et al.* [5], in an investigation of the effects of diffusional resistance on
94 wood char gasification in a tubular kiln reactor, reported no significant influence on
95 wood char gasification for mean char particle sizes of 0.1 mm and 0.47 mm. They
96 suggested that internal mass transfer effects at these conditions could be considered to
97 be negligible (experiments at T = 900 °C to 1000 °C, and steam partial pressure from
98 10.1 kPa to 70.9 kPa).

99 Mani *et al.* [13], in an investigation of reaction kinetics and mass transfer of
100 wheat straw char with CO₂ using a thermo gravimetric apparatus (TGA), found that
101 particle size (from less than 60 µm to 925 µm) had much influence on the char
102 gasification reaction, and reactivity decreased as the particle size increased (experiments
103 performed at T = 750 °C to 900 °C, with CO₂ partial pressure of 101 kPa).

104 Mermoud *et al.* [8] formed similar conclusions as Mani *et al.* [14]. However,
105 they investigated the steam gasification of single wood charcoal particles (10 mm to 30
106 mm in size) at different temperatures (830 °C to 1030 °C), and at different steam partial
107 pressures (10.1 kPa to 40.5 kPa). They concluded that internal mass transfer was
108 influencing the reaction under these operating conditions – although this is not
109 surprising as the charcoal particles were relatively large.

110

111 ***1.5. Effect of alkali and alkaline metallic (AAEM) species***

112

113 It is well-known that AAEM species can act as good catalysts for the
114 combustion and gasification of solid carbonaceous fuels such as biomass or biochar [1,
115 15]. As reported in Yip *et al.* [15], during char gasification, the reactivity of the raw
116 biochars generally increased, while that of all acid-treated biochars (for removal of
117 AAEM species) remained relatively unchanged with conversion. The results indicate
118 that Na, K, and Ca retained in the biochars were the key catalytic species, with the
119 catalytic effect appearing to be in the order $K > Na > Ca$ during the steam gasification
120 of the biochar.

121 A similar phenomenon of increased reactivity of biochar with conversion was
122 also observed and reported by Wu *et al.* [1]. The catalytic effect of the inherent AAEM
123 species seems in turn to depend on the carbon structure that probably affects the catalyst
124 dispersion. It was emphasized that the surface area of biochar increased with
125 conversion, suggesting the formation of new pores and/or opening of closed pores as a
126 result of steam activation during gasification. Besides the effect of the carbon structure
127 evolution, the inhibiting effect of some inorganic components such as Si and P was also
128 discovered by Hugnon *et al.* [16], where K would tend to be encapsulated by P and Si
129 with carbon conversion, and would then be unable to act as a catalyst.

130 Nevertheless, consideration of the effects of catalysts and evolution of carbon
131 structure during gasification will not be considered in any detail in this paper; however,
132 they will be used to explain the evolution of reactivity of RDF-derived char during the
133 gasification process.

134

135 ***1.6. Decisions taken***

136

137 Based on this review, it was decided that the influence of: char particle size, gas
138 flow, char bed length, reaction temperature and steam partial pressure should all be
139 explored. This would lead to the development of useful kinetic rate expressions, which
140 in the future could be used to help estimate the residence time required in a reactor to
141 achieve the desired conversion of carbon in the char. This work is clearly novel, as there
142 is relatively little information in the literature on the gasification kinetics of RDF-
143 derived char.

144 In developing the experimental technique, a number of important assumptions
145 were made based on the following:

146 (a) In the literature, it has been suggested (e.g. Everson *et al.* [17] and Huang *et al.*
147 [18]) that char-CO₂ and char-H₂O reactions proceed on separate active sites at
148 atmospheric pressure. Thus, in this present study, it was decided to study the
149 steam (H₂O) gasification of char as a set of experiments on their own.

150 (b) Although some authors (e.g. Everson *et al.* [17]; Huang *et al.* [18]) have
151 presented evidence of the inhibition effects of CO in CO₂-char reactions, and H₂
152 in steam-char reactions, in this study it is assumed that there are no inhibition
153 effects.

154 (c) The partial pressure of the gasifying agent (H₂O) is considered to remain
155 unchanged along the reactor, even though it is inevitably consumed in reality.
156 This assumption was also applied in other studies in the literature (e.g. Wu *et al.*
157 [7]; Yip *et al.* [15]).

158 (d) Many of the kinetic experiments on char gasification have been performed using
159 a TGA, and the carbon conversion was measured by the loss in the weight of the
160 sample [8, 14, 17, 18, 19]. However, in this study, it was decided to perform

161 such experiments in a small packed-bed reactor, which is often used in
162 heterogeneous catalytic experiments. A fast gas analysis method developed in
163 [20] using a quadrupole mass spectrometer (QMS) was used to measure the
164 product gas composition on-line, which was then used to calculate the rate of
165 carbon conversion in the char.

166

167 **2. Experimental Procedure**

168

169 *2.1. Experimental Apparatus*

170

171 The experimental work was carried out using a packed-bed reactor (Figure 1),
172 which operated at atmospheric pressure. The reactor consisted of a vertical stainless
173 steel tube with an inner diameter of 15.6 mm, which was filled with RDF-derived char
174 particles. The char bed depth could be varied from 1.6 mm to 23.7 mm. This tube was
175 positioned inside an electrically heated furnace, and the temperature inside the char bed
176 was measured using a thermocouple located at the top of the char bed. The char bed was
177 supported by two quartz wool layers which retained the char and ash particles.

178 In experiments with steam, the water and nitrogen passed through a stainless steel tube
179 put inside the furnace, which vaporized the water and preheated the gas. The nitrogen
180 flow was adjusted with a rotameter, while that of the water was set using a metering
181 pump.

182 The gas exiting from the top of the reactor flowed through a cooling coil, and
183 condensate was trapped in two plastic vessels (connected in series). The gas then passed
184 through a glass wool filter, and was finally discharged into the vent from the fume

185 cupboard. A gas sample stream was passed to a quadrupole mass spectrometer (QMS)
186 for on-line gas analysis.

187

188 *Figure 1 here*

189

190 **2.2. RDF-derived Char Particle Size Distribution**

191

192 Sieves were used to classify by size the RDF-derived char that had been
193 obtained from the commercial pilot-scale gasifier. Information on the fixed carbon
194 content in the different char size ranges will be also useful when designing a process.

195 The frequency mass fractions were calculated from:

$$196 \quad q_i = \left(\frac{m}{\Delta d_q} \right)_i \quad \text{or} \quad Q_i = \sum_1^i (q \Delta d_q)_i \quad (1)$$

197 where: q_i is the differential frequency mass (or fixed carbon content) fraction of size
198 interval i , μm^{-1} ; Q_i is the cumulative frequency mass (or fixed carbon content) fraction
199 of particles smaller than size $(d_q)_i$; $(\Delta d_q)_i$ is the size interval i , μm ; and m_i is the mass
200 fraction of char particle in size interval i .

201 Then, the mean size of the RDF-derived char particles was estimated from:

$$202 \quad \bar{d}_q = \frac{1}{\sum_{all\ i} (m/d_q)_i} = 305.52 \mu\text{m} \quad (2)$$

203 The results of such a char particle distribution are presented, in Figure 2, from
204 which it can be seen that particle size varied from $37.5 \mu\text{m}$ to $7,000 \mu\text{m}$. As the mean
205 size of the RDF-derived char was $305 \mu\text{m}$, a sieve was used to obtain a char particle size
206 range of 250 to $500 \mu\text{m}$ (representing mean particle size), and this size range was used
207 for the experiments.

208

209 *Figure 2 here*

210

211 From the data on the fixed carbon content (Figure 2(c)), it is interesting to note
212 that this changes slightly with particle size, and this is most probably related to the part
213 of the process from which that carbon particle arose (e.g. carried in the gas stream and
214 trapped in a cyclone, or retained in the char stream from the base of the gasifier).

215 The results of proximate analysis of the RDF-derived char are: moisture 4.59
216 wt.% wet basis; volatiles 10.71 wt.% dry basis; fixed carbon 34.18 wt.% dry basis; ash
217 55.10 wt.% dry basis. The proximate analysis of the RDF pellets was also performed,
218 giving: moisture 7 wt.% wet basis; volatiles 43 wt.% dry basis; fixed carbon 31 wt.%
219 dry basis; ash 26 wt.% dry basis.

220 From these measurements, it was decided to use char in the size range of 250
221 μm to 500 μm for the kinetic experiments.

222

223 **2.3. Experimental Methodology**

224

225 A bucket of RDF-derived char, obtained from an actual gasification pilot-plant
226 that used RDF pellets as fuel, was supplied by Refgas Ltd, Sandycroft. This char was
227 sealed and stored at room temperature, and used throughout this study to ensure the
228 repeatability of the char resource.

229 Samples of char were first conditioned by heating for 3 hours in a flow of N_2 at
230 800 °C, and this removed any volatiles (checked with the QMS). Then N_2 was fed into
231 the reactor (during the heating-up period) to achieve the desired operating temperature.

232 This was then followed by the addition of water which turned into steam, and the
233 experiment was started. The system pressure was atmospheric (open end of reactor).
234 After each run, air was passed through the reactor to burn out any residual carbon.
235 Finally, the reactor was cooled, and the remaining ash was collected and weighed.

236 The rate of carbon conversion in the char can be inferred from the molar flow
237 rate of CO and CO₂ from the reactor. This approach has been used in many studies [5, 6,
238 7, 9, 10], making use of the flow of an inert sweeping gas (e.g. N₂ or Argon) to perform
239 such calculations. If the formation of CH₄ was significant then it would have to be
240 included, but this was checked and found not to be the case in the experiments
241 described.

242 The experimental conversion of carbon in the char, X , may be defined (e.g. in
243 Paviet *et al.*[5]) as:

$$244 \quad X = \frac{w_0 - w}{w_0 - w_{ash}} \quad (3)$$

245 where: w_0 is the initial sample weight, w is the sample weight at any time t and w_{ash} is
246 the ash content measured after reaction.

247 The evolution of sample weight, $w(t)$, as a function of time is unknown, but it
248 can be deduced from the gas composition. The experimental kinetic rate, at any time t ,
249 can thus be calculated (e.g. in Cozzani [19]) from:

$$250 \quad \frac{dX}{dt} = \lim_{\Delta t \rightarrow 0} \left(\frac{X_{t_2} - X_{t_1}}{\Delta t} \right) \quad (4a)$$

251 where: X_{t_1} and X_{t_2} are carbon conversion at time t_1 and t_2 , respectively; and

252 $\Delta t = t_2 - t_1 \approx 20$ s, which is the measurement step of the gas analysis method.

253 or (e.g. in Paviet *et al.* [5]) from:

254
$$\frac{dX}{dt} = \frac{12(F_{CO} + F_{CO_2})}{w_0 - w_{ash}} \quad (4b)$$

255 where: F_{CO} and F_{CO_2} are molar flow rates (mol/min) of CO and CO₂, respectively, in
256 the gas stream from the packed bed.

257 Both Equations (4a) and (4b) were tested, and they produced the same results.

258 Equation (4b) was used in this work.

259

260 **3. Results and Discussion**

261

262 ***3.1. Experimental Results***

263 To determine the operating conditions for the kinetic study the following set of
264 preliminary experiments was performed:

265

266 *3.1.1. Effect of char bed length*

267 First of all, some preliminary experiments were performed with different char
268 bed lengths (1.6 mm, 5.7 mm, 8.2 mm, 16.8 mm and 23.7 mm), corresponding to
269 different initial mass quantities of char (0.1 g, 0.35 g, 0.5 g, 1.03 g and 1.45 g). The bulk
270 density of the char is 500 kg m⁻³. Experiments were performed at: furnace temperature
271 set at 900 °C; char particles from 250 μm to 500 μm; N₂ flow set at 0.2 L min⁻¹ (1 L = 1
272 dm³; 1 min = 60 s); H₂O flow set at 0.148 g min⁻¹; and an calculated molar ratio of
273 H₂O:N₂ = 1:1.

274 It was observed that the performance of the reactor with bed lengths from 1.6
275 mm to 16.8 mm was very similar and about 70 % of the carbon in the char was

276 consumed after eight minutes. This means that in such a sample the resistance to
277 external mass transfer is negligible.

278 For the planned kinetics study, it was decided to select a small initial bed length
279 to reduce any secondary reactions, and to minimize the change in the partial pressure of
280 steam along the char bed. However, if a bed length < 5.7 mm was used, then CO
281 concentration would be low, leading to measurement errors. Therefore, an initial char
282 bed length of 8.2 mm was selected for all subsequent experiments.

283

284 3.1.2. *Effect of gas flow*

285 Experiments were performed at different gas inlet flows ($N_2 = 0.2$ L min^{-1} , 0.4 L
286 min^{-1} , 0.6 L min^{-1} and 0.7 L min^{-1} ; $H_2O = 0.148$ g min^{-1} , 0.296 g min^{-1} , 0.444 g min^{-1}
287 and 0.518 g min^{-1}), which corresponded to different superficial velocities in the packed
288 bed (0.218 m s^{-1} , 0.437 m s^{-1} , 0.655 m s^{-1} and 0.764 m s^{-1}). The experiments were done
289 at the following conditions: furnace temperature set at 900 °C; char bed length = 8.2
290 mm; char particles from 250 μm to 500 μm ; calculated molar ratio of $H_2O:N_2 = 1:1$.

291 It was observed that at the high gas superficial velocities (0.437 m s^{-1} to 0.764 m
292 s^{-1}), the gas velocity has little influence on char gasification, indicating that external
293 mass transfer resistance is low. In Pavier *et al.* [5], superficial gas velocities at 10 cm s^{-1}
294 to 20 cm s^{-1} (0.1 m s^{-1} to 0.2 m s^{-1}) had little influence on external mass transfer.

295 Although high gas velocities are preferred, this leads to higher errors in CO
296 measurements in the outlet gas stream; hence, a gas velocity of 0.218 m s^{-1} was selected
297 for subsequent experiments.

298

299 3.1.3. *Effect of char particle size*

300 Experiments were performed with char particles that had the following size
301 ranges: 180 μm to 250 μm ; 250 μm to 500 μm ; 1000 μm to 1180 μm ; and 2000 μm to
302 4000 μm . The experiments were done at: furnace temperature set at 900 $^{\circ}\text{C}$; char bed
303 length = 8.2 mm; N_2 flow set at 0.2 L min^{-1} ; H_2O flow set at 0.148 g min^{-1} ; calculated
304 molar ratio of $\text{H}_2\text{O}:\text{N}_2 = 1:1$.

305 The results obtained showed that the rate of carbon conversion increases slightly
306 as the particle size was reduced. However, the increase was insignificant in the size
307 range tested. Also, because the measured mean particle size of RDF-derived char was
308 approximately 305 μm , particles in the range of 250 μm to 500 μm were chosen for the
309 subsequent kinetic experiments.

310

311 *3.1.4. Effect of Reaction Temperature*

312 To explore the effect of reaction temperature, experiments were performed at:
313 800 $^{\circ}\text{C}$, 850 $^{\circ}\text{C}$ and 900 $^{\circ}\text{C}$. This set of experiments (at different reaction temperature)
314 was repeated at various H_2O flows, while N_2 flow was kept constant at 0.2 L min^{-1} . This
315 helps to determine kinetic parameters that will be described later. One example of the
316 conditions in the reactor for one set of experiments was: N_2 flow rate = 0.2 L min^{-1} ; char
317 bed length = 8.2 mm; H_2O flow = 0.222 g min^{-1} ; calculated molar ratio of $\text{H}_2\text{O}:\text{N}_2 = 3:2$,
318 corresponding to steam partial pressure of 60 kPa.

319 As expected, reaction rates increased with temperature, see Figure 3.

320

321 ***Figure 3 here***

322

323 *3.1.5. Effect of Partial Pressure of Steam*

324 As a reminder, for each reaction temperature (800 °C, 850 °C, or 900 °C),
325 experiments were performed at different partial pressures of H₂O (33.3 kPa, 50 kPa, 60
326 kPa and 66.7 kPa), which corresponded to different H₂O flows (0.074 g min⁻¹, 0.148 g
327 min⁻¹, 0.222 g min⁻¹ and 0.296 g min⁻¹), while N₂ flow was kept constant at 0.2 L min⁻¹.
328 One example of the conditions in the reactor was: furnace temperature set = 850 °C; N₂
329 flow = 0.2 L min⁻¹; char bed length = 8.2 mm.

330 The results are presented in Figure 4, for experiments performed at 850 °C.
331 From these experiments, char reactivity increases with steam partial pressure.

332

333 *Figure 4 here*

334

335 **3.2. Kinetic Analysis**

336

337 There are several well established approaches which can be used to develop a
338 model to describe reacting char. Because the ash content in the RDF-derived char is
339 high, then according to Levenspiel [21] and Kunii and Levenspiel [22], then either the
340 Uniform-Reaction Model or the Shrinking-Core Model for porous solids of unchanging
341 size could be applied. In general, small particles follow the Uniform-Reaction Model,
342 while large particles follow the Shrinking-Core Model - with ash diffusion controlling at
343 high temperatures, but reaction controlling at low temperatures [22]. In this study, both
344 of these models were considered.

345

346 *3.2.1. Estimate of Kinetic Parameters for the Shrinking-Core Model*

347 The theoretical development of this model is based on Levenspiel [21] and
348 Kunni and Levenspiel [22]. In summary: for a Shrinking-Core model, the reaction front
349 advances from the outer surface into the particle, leaving behind a layer of ash. Thus, at
350 any time there exists an unreacted core of carbon which shrinks in size during the
351 reaction. The driving force of the gasification is proportional to the available surface
352 area, and char reactivity of a batch particle can be defined as:

$$353 \quad r = \frac{1}{(1-X)^{2/3}} \frac{dX}{dt} = k.P_{H_2O}^n \quad (5)$$

354 where: $r = \frac{1}{(1-X)^{2/3}} \frac{dX}{dt}$ is called specific (or apparent) reactivity of char in
355 gasification reaction [15].

356 A similar equation to Equation (5) can also be seen in the literature (e.g.
357 Liliedahl and Sjoström [23]; Basu [24]).

358 For the steam gasification of char, an n^{th} -order reaction model is commonly used
359 [6, 24]:

$$360 \quad r = k.P_{H_2O}^n \quad (6)$$

361 where: P_{H_2O} is the partial pressure of steam, that is considered as the partial pressure of
362 steam in the inlet gas stream.

363 From the experimental data of carbon conversion rate, the values of the rate
364 constant k , the reaction order n , apparent activation energy E and pre-exponential factor
365 A were calculated. Figure 5 shows an example of the plots to determine the values of k
366 and n at 850 °C, and E and A at different degrees of conversion (X). These results are
367 very encouraging as the data points are positioned close to the ‘best-fit’ straight lines.
368 Values of k and n , E and A are shown in Tables 1 and 2, respectively. From these, the

369 apparent activation energy varied from 96 to 106 kJ mol⁻¹ across the 10 % to 70 %
370 conversion range, and then it increased dramatically to 152 kJ mol⁻¹ at 80 % carbon
371 conversion.

372

373 **Figure 5 here**

374 **Table 1 here**

375 **Table 2 here**

376

377 Blasi [12] reviewed data on the steam gasification of a number of different
378 biochars, and reported that E varied from 143 to 237 kJ mol⁻¹ (with a large part of the
379 values around 180 to 200 kJ mol⁻¹), depending on reaction conditions and biochar
380 source. This indicates that the RDF-derived char used in this study may be very active.

381 From data in Table 2, the value of the pre-exponential factor increases slightly
382 with conversion across the 10 % to 70 % range, but more rapidly after that. This change
383 may be due to the evolution of the char structure with carbon conversion. Ahmed and
384 Gupta [6] suggested that ash might have increased the adsorption rate of steam to the
385 char surface, leading to an increase in the pre-exponential factor. However, (a)
386 increased porosity, and (b) access to the ash (which may have catalytic and inhibiting
387 properties), may also have a role to play [1, 7]. The effects of carbon structure on char
388 reactivity are also discussed in Aarna and Suuberg [25], where they concluded that the
389 micropores (< 2 nm) probably did not participate in the gasification reaction of chars,
390 and that the surface developed by the macropores and the mesopores (2 nm < diameter
391 < 50 nm) was a better indicator of the reactive surface, than the total pore surface area.
392 This conclusion is consistent with others (e.g. Paviet *et al.* [5]; Mermoud *et al.* [26])

393 In other studies on the steam gasification of biochars [1, 6, 8, 15, 27] pore
394 surface area and reactivity of chars increased with conversion, while an opposite trend
395 was observed for the steam gasification of coal chars [7, 23, 28].

396 It was decided, to examine the 70 % to 80 % carbon conversion region in more
397 detail, and more data points were added. Figure 5(c) shows the Arrhenius plot for
398 conversions from 71 % to 80 %. A ‘compensation effect’ is observed here, where there
399 is a simultaneous increase in apparent activation energy and pre-exponential factor with
400 conversion, see Table 2. This ‘compensation effect’ or ‘isokinetic effect’ has been
401 observed and reported in the literature for char-gas reactions [6, 7], and explains the
402 observed change that took place.

403

404 *3.2.2. Estimate of kinetic parameters for the Uniform-Reaction Model*

405 For the Uniform-Reaction Model, the driving force for the gasification is
406 proportional to the mass of unreacted carbon in the particle, and char reactivity of a
407 batch particle can be defined as:

$$408 \quad r = \frac{1}{1-X} \frac{dX}{dt} = k \cdot P_{H_2O}^n \quad (7)$$

409 A similar equation to Equation (7) can also be seen in the literature [22, 23, 24].

410 For this model, the values of the apparent activation energies (E) and pre-
411 exponential factors (A) at different degrees of conversion (X) are calculated and
412 presented in Table 3.

413

414 **Table 3 here**

415

416 It is interesting to note, that when comparing the values of the apparent
417 activation energy (E) calculated in Table 3 (Uniform-Reaction Model), with the values
418 in Table 2 (Shrinking-Core Model), then very similar results have been obtained. This
419 means, that the two models would produce very similar results across the range of
420 conditions tested. However, values of the pre-exponential factor (A) in the Uniform-
421 Reaction Model are different from those in the Shrinking-Core Model. Mathematically,
422 this comes from the fact that the pre-exponential factor in Shrinking-Core Model
423 includes the factor that is a function of the density of carbon and diameter of the char
424 particles, whereas that in the Uniform-Reaction Model does not (deduced from Kunii
425 and Levenspiel [22]).

426

427 **3.3. Comparison between RDF-derived char and wood charcoal**

428

429 Finally, a few experiments were performed using a wood based charcoal,
430 obtained from a small commercial gasification reactor that used wood chips as fuel. A
431 bucket of this char, supplied by Refgas Ltd, Sandycroft, was sealed and stored at room
432 temperature, and used throughout this study to ensure the repeatability of this char
433 resource. Two different ranges of wood charcoal particles were used (250 μm to 500
434 μm and 2000 μm to 4000 μm) and tested. All of these experiments were performed at:
435 furnace temperature set at 900 $^{\circ}\text{C}$; char bed length = 8.2 mm; N_2 flow set at 0.2 L min^{-1} ;
436 H_2O flow set at 0.148 g min^{-1} ; calculated molar ratio of $\text{H}_2\text{O}:\text{N}_2 = 1:1$.

437 The results are shown in Figure 6.

438

439 ***Figure 6 here***

440

441 From these data, it is clear that at low carbon conversion (< 60 %), the RDF-
442 derived char is much more reactive than wood charcoal. However, at higher carbon
443 conversions the opposite is true.

444 In some studies [15, 28], the reactivity of gasification of char is presented as the
445 specific (or apparent) reactivity, r . If the Shrinking-Core Model is selected, then

446 $r = \frac{1}{(1-X)^{2/3}} \frac{dX}{dt}$. Figure 6(c) shows the evolution of apparent reactivity of char with

447 carbon conversion.

448 From Figure 6(c), above a carbon conversion of 60 %, the apparent RDF-derived
449 char reactivity decreases sharply with carbon conversion. This behaviour of RDF-
450 derived char is opposite to that of other biochars such as mallee-biomass-derived char
451 [14] or food-waste-derived char [6]; however, it is similar to that of coal char (e.g. as
452 presented in Wu *et al.* [7]; Liu *et al.* [9]; Liliedahl and Sjoström [22]; Xu *et al.* [27]).

453 Mermoud *et al.* [8], in a study of steam gasification of single wood charcoal
454 particles (with a diameter of 10 mm to 30 mm), observed that the reactivity of wood
455 charcoal increased continuously with conversion due to a continuous increase in the
456 surface area. However, Liu *et al.* [9] reported a decrease in coal char reactivity with
457 conversion because of a decrease in the surface area.

458 The RDF-derived char contained 55 wt.% ash, which consisted of inorganic
459 elements. It is well known that these elements can have a catalytic effect, which could
460 be the main reason for the increase in reactivity at low carbon conversion (<60%).
461 However, the presence of inorganic elements can also decrease the porosity to such an
462 extent that the active surface area is also decreased [1, 6, 7, 12]. In addition, Hugnon *et al.* [16] noticed that during steam gasification of algal and lignocellulosic biomass, K

464 would tend to be encapsulated by P and Si with carbon conversion, and would then be
465 unable to act as a catalyst. Therefore, from the results obtained in this paper, at higher
466 (>60%) carbon conversion, a higher ash content is expected, which could result in an
467 encapsulation of AAEM species, a decrease in porosity (and active surface area), and
468 hence reactivity.

469

470 **4. Conclusions**

471

472 For the steam gasification of the RDF-derived char, the apparent activation
473 energy E varied from 96 kJ mol⁻¹ to 162 kJ mol⁻¹. The reactivity of the char (at carbon
474 conversions from 10 % to 60 %) appears to be higher than other biochars reported in the
475 literature. However, at high conversions (> 60 %), the apparent reactivity of the RDF-
476 derived char decreases with carbon conversion, behaving in a similar manner to coal
477 structures.

478 Comparisons between the use of the Shrinking-Core Model and the Uniform-
479 Reaction Model produced almost identical results.

480 Information has been presented in this paper, which provides data on the
481 properties of an RDF-derived char and how it could be gasified in the presence of
482 steam. This supports the viability of converting this type of char into a useful fuel gas,
483 which would enhance the commercial viability of the overall 'RDF to energy' process.
484 Such data on RDF-derived char are scarce in the literature, and this is probably the first
485 detailed kinetic study of its type in which kinetic parameters for an RDF-derived char
486 have been determined. These parameters could be used in modelling studies to explore

487 different design concepts (e.g. packed-bed, moving-bed, fluidized bed) for the ‘char-
488 gasifier’, although they would of course then need to be tested in pilot-scale studies.

489

490 **Acknowledgment**

491

492 We are grateful for the support received from Refgas Ltd a company developing
493 biomass to energy processes, and also for the support from the Vietnam Ministry of
494 Education & Training, in the form of a research grant for C. D. Le.

495

496 **Nomenclature**

497

498	A	Pre-exponential factor	$\text{bar}^{-n} \text{s}^{-1}$
499	d_q	Diameter of char particle	μm
500	\bar{d}_q	Mean char particle diameter	μm
501	$(\Delta d_q)_i$	Char particle size interval i	μm
502	E	Activation energy	kJ mol^{-1}
503	F_i	Molar flow rate of species i	mol/min
504	k	Specific (or apparent) reaction rate coefficient	$\text{bar}^{-n} \text{s}^{-1}$
505	m_i	Mass fraction of char particle in size interval i	
506	n	Reaction order	
507	P_{H_2O}	Partial pressure of steam	bar(a)
508	q	Differential frequency mass (or fixed carbon content)	
509		distribution of char particle size	μm^{-1}
510	q_i	Differential frequency mass (or fixed carbon	

511		content) fraction of size interval i	μm^{-1}
512	Q	Cumulative frequency mass (or fixed carbon content)	
513		distribution of char particle size	
514	Q_i	cumulative frequency mass fraction of particles smaller	
515		than size $(d_q)_i$	
516	r	Specific (or apparent) reactivity of char in gasification	s^{-1}
517	R_g	Universal gas constant	$8.314 \text{ J.mol}^{-1} \text{ K}^{-1}$
518	t	Time	s
519	Δt	Time interval	s
520	T	Temperature	$^{\circ}\text{C}$
521	w	Char sample weight at any reaction time t	g
522	w_0	Initial char sample weight	g
523	w_{ash}	Ash content measured after gasification reaction of char	g
524	X	Carbon conversion at any reaction time t	$\%$

525

526 **References**

- 527 [1] Wu H, Yip K, Tian F, Xie Z, Li CZ. Evolution of char structure during the steam
528 gasification of biochars produced from the pyrolysis of various mallee biomass
529 components. Ind. Eng. Chem. Res. 2009; 48(23): 10431-10438.
- 530 [2] Knoef HAM, editor. Handbook Biomass Gasification. BTG biomass technology
531 group; 2005.
- 532 [3] Chaudhari ST, Dalai AK, Bakhshi NN. Production of Hydrogen and/or Syngas
533 ($\text{H}_2 + \text{CO}$) via steam gasification of biomass-derived chars. Energy and Fuel 2003;
534 17(4): 1062-1067.

- 535 [4] Kolaczkowski S, Le CD, Jodlowski P. Gasification of wood pellets in an
536 experimental quartz tube gasifier – How visual 1D experiments can aid 3D design
537 considerations. In Proceedings of the bioten conference on biomass and biofuels
538 2010, Bridgwater AV, editor, CPL Press UK; 2011, p. 720-732.
- 539 [5] Paviet F, Bals O, Antonini G. The effects of diffusional resistance on wood char
540 gasification. *Process Safety and Environment Protection* 2008; 86: 131-140.
- 541 [6] Ahmed II, Gupta AK. Pyrolysis and gasification of food waste: Syngas
542 characteristics and char gasification kinetics. *Applied Energy* 2010; 87: 101-108.
- 543 [7] Wu S, Wu J, Li L, Wu Y, Gao J. The reactivity and kinetics of yanzhou coal chars
544 from elevated pyrolysis temperatures during gasification in steam at 900-1200°C.
545 *Trans IChemE, Part B, Process Safety and Environmental Protection* 2006; 84(B6):
546 420-428.
- 547 [8] Mermoud F, Golfier F, Salvador S, Van de Steene L, Dirion JL. Experimental and
548 numerical study of steam gasification of a single charcoal particle. *Combustion
549 and Flame* 2006; 145: 59-79.
- 550 [9] Liu H, Luo C, Kato S, Uemiya S, Kaneko M, Kojima T. Kinetics of CO₂
551 gasification at elevated temperatures. Part I: Experimental results. *Fuel Processing
552 Technology* 2006; 87: 775-781.
- 553 [10] Paviet F, Bals O, Antonini G. Kinetic study of various chars steam gasification.
554 *International Journal of Chemical Reactor Engineering* 2007; 5: Article A80.
- 555 [11] Khor A, Ryu C, Yang Y, Sharifi VN, Swithanbank J. Clean Hydrogen Production
556 via Novel Steam-Air Gasification of Biomass. WHEC 16/13-16. Lyon France;
557 2006.

- 558 [12] Blasi CD. Combustion and gasification rates of lignocellulosic chars. *Process in*
559 *Energy and Combustion Science* 2009; 35: 121-140.
- 560 [13] Dupont C, Boissonnet G, Seiler JM, Gauthier P, Schweich D. Study about the
561 kinetic processes of biomass steam gasification. *Fuel* 2007; 86: 32-40.
- 562 [14] Mani T, Mahinpey N, Murugan P. Reaction kinetics and mass transfer studies of
563 biomass char gasification with CO₂. *Chemical Engineering Science* 2011; 66: 36-
564 41.
- 565 [15] Yip K, Tian F, Hayashi J, Wu H. Effect of alkali and alkaline earth metallic
566 species on biochar reactivity and syngas composition during steam gasification.
567 *Energy Fuels* 2010; 24: 173-181.
- 568 [16] Hognon C, Dupont C, Grateau M, Delrue F. Comparison of steam gasification
569 reactivity of algal and lignocellulosic biomass: Influence of inorganic elements.
570 *Bioresource Technology* 2014; 164: 347-353.
- 571 [17] Everson RC, Neomagus HWJP, Kasaini H, Njapha D. Reaction kinetics of
572 pulverized coal-chars derived from inertinite-rich coal discards: Gasification with
573 carbon dioxide and steam. *Fuel* 2006; 85: 1076-1082.
- 574 [18] Huang Z, Zang J, Zhao Y, Zhang H, Yue G, Suda T, Narukawa M. Kinetic studies
575 of char gasification by steam and CO₂ in the presence of H₂ and CO. *Fuel*
576 *Processing Technology* 2010; 91: 843-847.
- 577 [19] Cozzani V. Reactivity in oxygen and carbon dioxide of char formed in the
578 pyrolysis of refuse-derived fuel. *Ind. Eng. Chem. Res.* 2000; 39: 864-872.
- 579 [20] Le, C.D., Kolaczowski, S. and McClymont, D.W.J. Using a quadrupole mass
580 spectrometer for on-line gas analysis – gasification of biomass and refuse derived
581 fuel. *Fuel*. 2015; 139: 337-345.

- 582 [21] Levenspiel O. Chemical Reaction Engineering. 3rd ed. John Wiley & Sons; 1999.
- 583 [22] Kunii D, Levenspiel O. Fluidization Engineering. 2nd ed. Butterworth-
584 Heinemann; 1991.
- 585 [23] Liliedahl T, Sjostrom K. Modeling of char-gas reaction kinetics. Fuel 1997; 76(1):
586 29-37.
- 587 [24] Basu P. Biomass Gasification and Pyrolysis. Elsevier Inc; 2010.
- 588 [25] Aarna I, Suuberg EM. Change in reactive surface area and porosity during char
589 oxidation. Twenty-Seventh Symposium (International) on Combustion/The
590 Combustion Institute ;1998, p. 2933-2939.
- 591 [26] Mermoud F, Salvador S, Van de Steene L, Golfier F. Influence of the pyrolysis
592 heating rate on the steam gasification rate of large wood char particles. Fuel 2006;
593 85: 1473-1482.
- 594 [27] Golfier F, Van de steene L, Salvador S, Mermoud F, Oltean C, Bues MA. Impact
595 of peripheral fragmentation on the steam gasification of an isolated wood charcoal
596 particle in a diffusion-controlled regime. Fuel 2009; 88: 1498–1503.
- 597 [28] Xu Q, Pang S, Levi T. Reaction kinetics and producer gas compositions of steam
598 gasification of coal and biomass blend chars, part 1: Experimental investigation.
599 Chemical Engineering Science 2011; 66: 2141-2148.
- 600

601 **Figure Captions**

602

603 **Figure 1.** Schematic of the kinetic study apparatus.

604 **Figure 2.** RDF-derived char particles: (a) differential frequency mass and fixed carbon
605 content distributions, (b) cumulative frequency mass and fixed carbon content
606 distributions, (c) fixed carbon content based on char particle size.

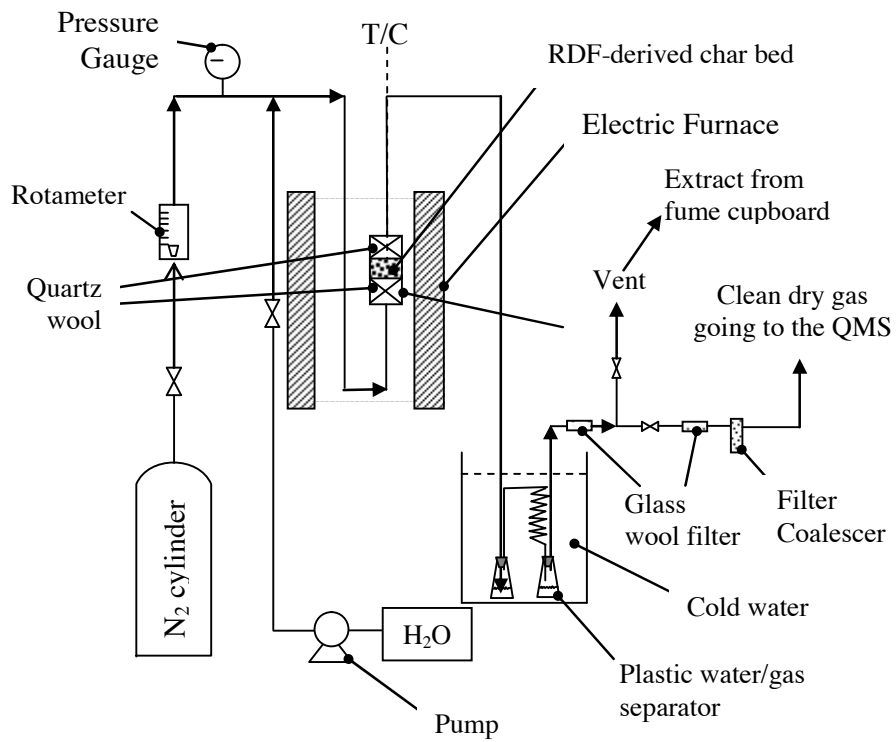
607 **Figure 3.** Influence of reaction temperature: (a) carbon conversion, (b) rate of carbon
608 conversion.

609 **Figure 4.** Influence of steam partial pressure at 850 °C: (a) carbon conversion, (b) rate
610 of carbon conversion.

611 **Figure 5.** Plots to estimate kinetic values: (a) Example of plot to determine the values of
612 k and n at 850 °C (Shrinking-Core Model); (b) Arrhenius plot for conversions from 10
613 to 80 % (Shrinking-Core Model); (c) Arrhenius plot for conversions from 71 to 80 %
614 (Shrinking-Core Model).

615 **Figure 6.** Comparisons between RDF-derived char and wood charcoal at 900 °C: (a)
616 carbon conversion, (b) rate of carbon conversion, (c) apparent reactivity.

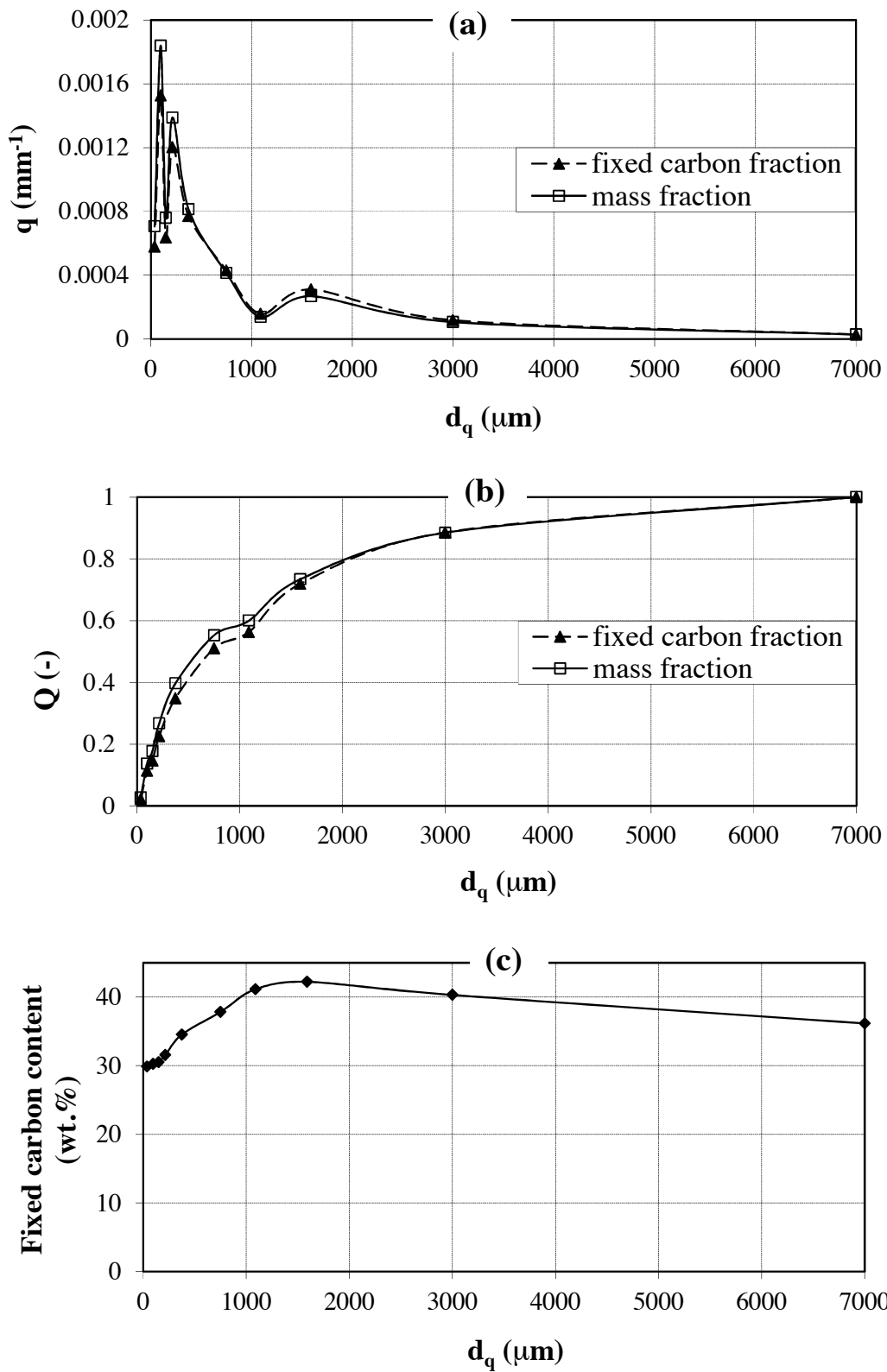
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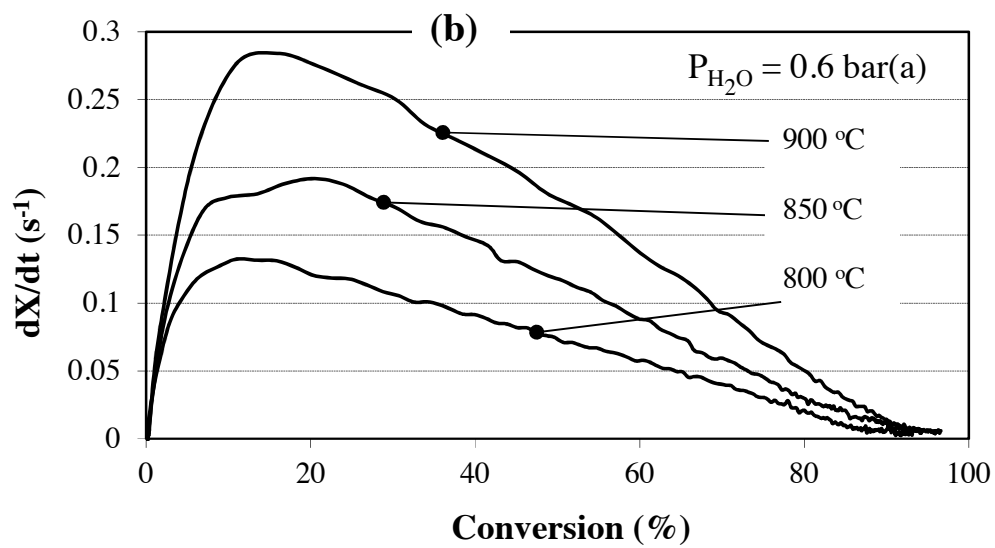
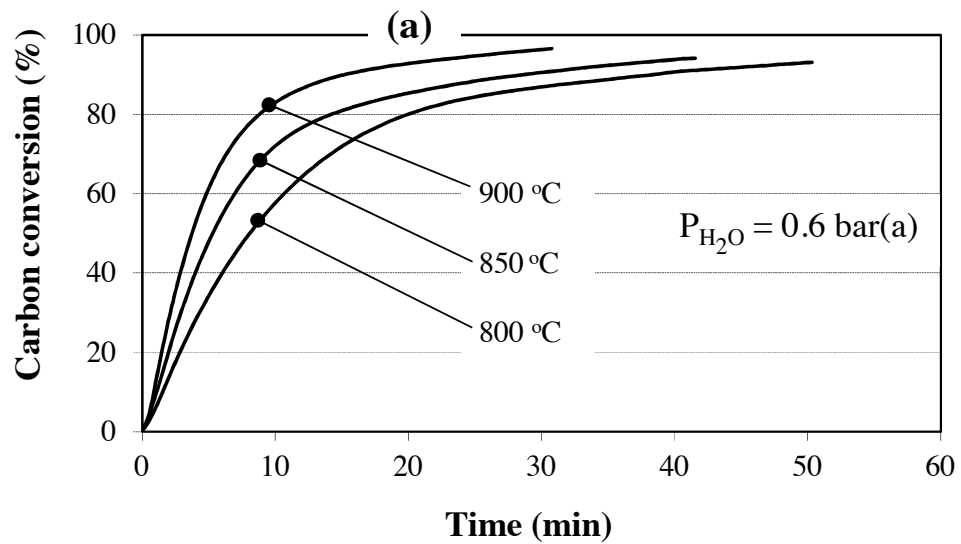
619 **Figure 1**

620



621

622 **Figure 2**

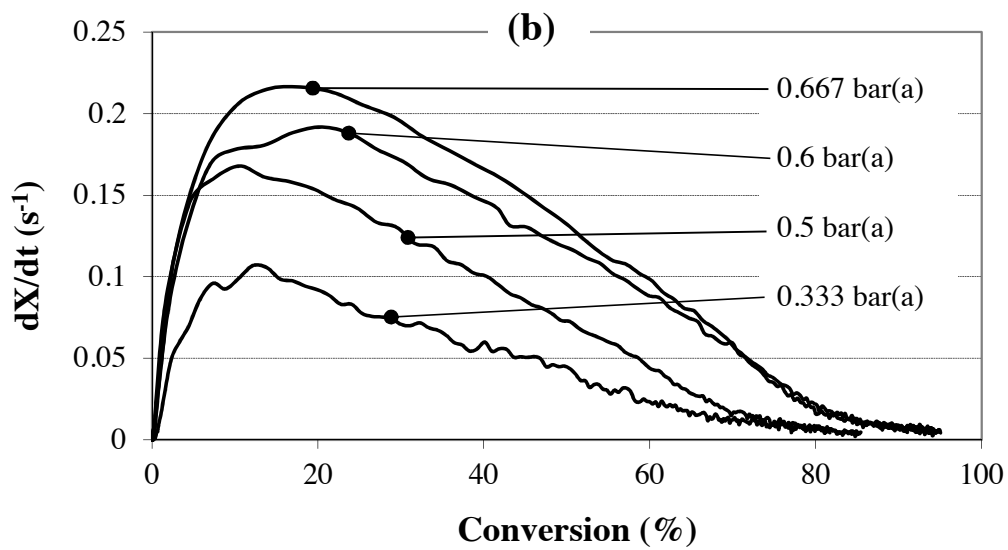
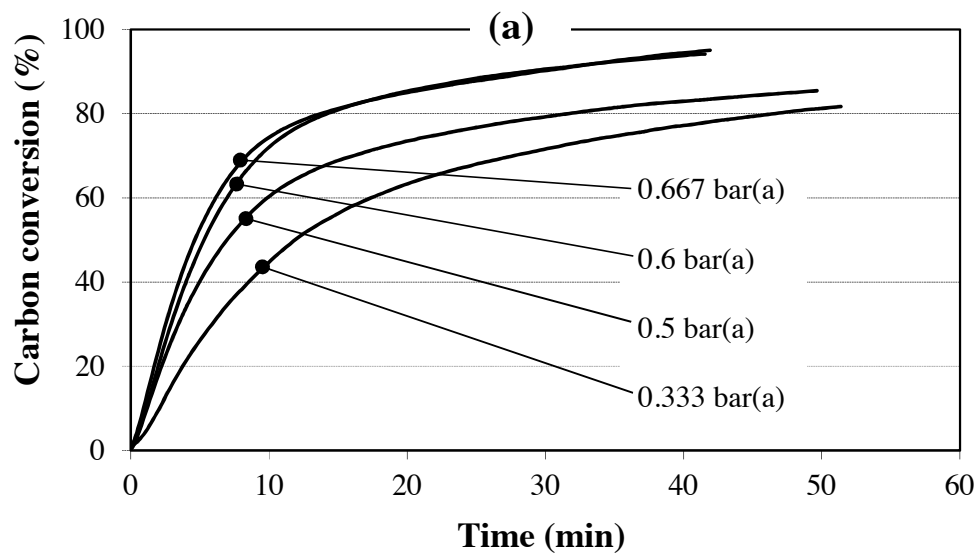


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624 **Figure 3**

625

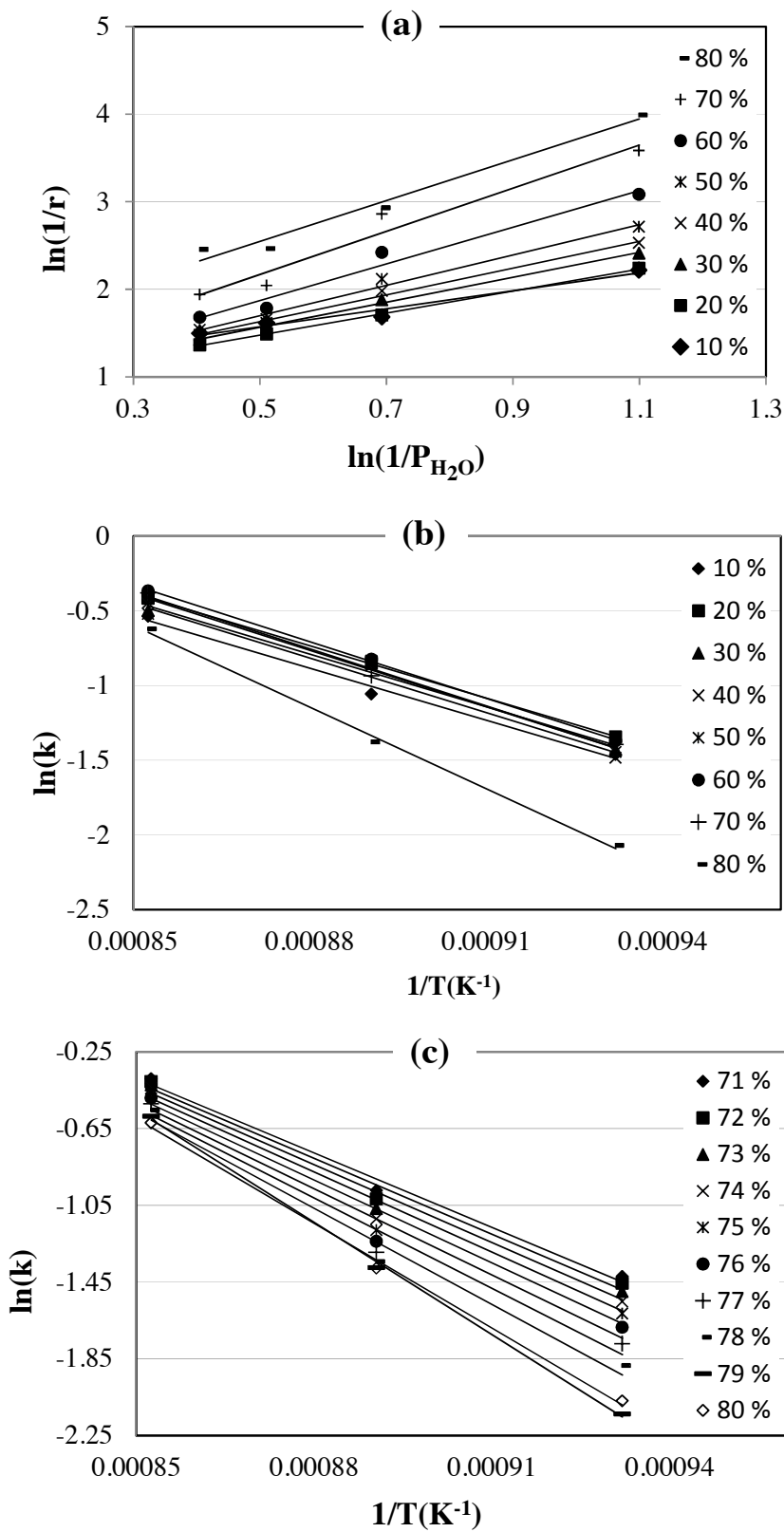
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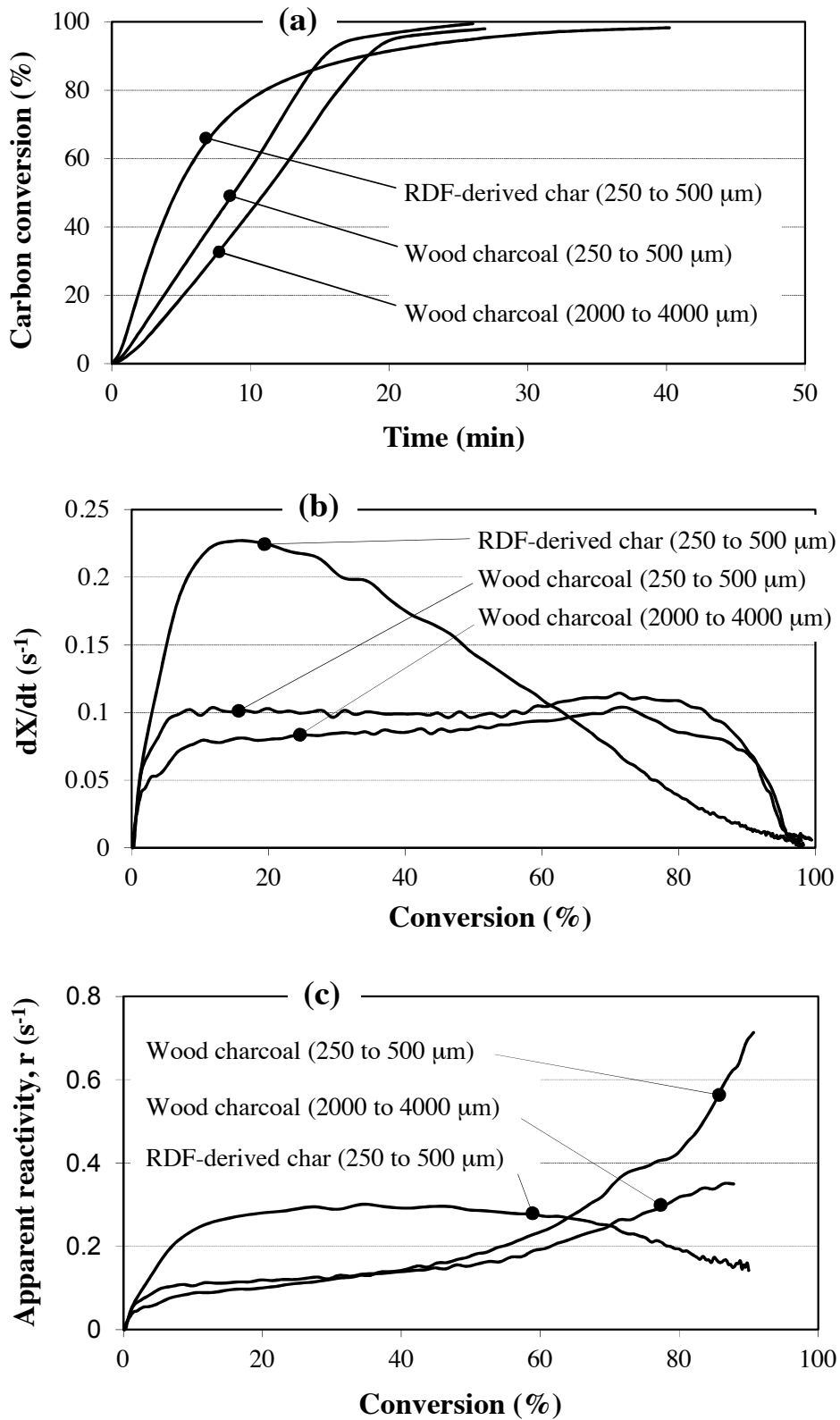
628 **Figure 4**

629



630

631 **Figure 5**



632

633 **Figure 6**

634 **Table 1.** Values of k and n at various reaction temperatures (Shrinking-Core Model).

Carbon conversion (%)	900 °C		850 °C		800 °C	
	<i>k</i>	<i>n</i>	<i>k</i>	<i>n</i>	<i>k</i>	<i>n</i>
10	0.585	1.453	0.347	1.025	0.232	0.889
20	0.660	1.413	0.429	1.261	0.261	1.075
30	0.607	1.370	0.427	1.429	0.239	1.179
40	0.594	1.409	0.421	1.529	0.226	1.216
50	0.639	1.579	0.435	1.732	0.235	1.382
60	0.693	1.878	0.439	2.092	0.254	1.810
70	0.684	2.286	0.393	2.466	0.248	2.351
80	0.537	2.676	0.252	2.333	0.126	2.937

635

636

637 **Table 2.** Apparent activation energies and pre-exponential factors (Shrinking-Core
 638 Model).

Carbon conversion (%)	Arrhenius equation $\ln(k) = \ln(A) - \frac{E}{R_g} \frac{1}{T}$	Apparent activation energy, E (kJ mol⁻¹)	Pre-exponential factor, A (bar⁻ⁿ s⁻¹)
10	y=9.342 – 11620x	96.6	1.14 x 10 ⁴
20	y=9.5596 – 11696x	97.2	1.42 x 10 ⁴
30	y= 9.5651 – 11768x	97.8	1.43 x 10 ⁴
40	y= 9.9045 – 12182x	101	2.00 x 10 ⁴
50	y=10.323 – 12597x	105	3.04 x 10 ⁴
60	y=10.42 – 12644x	105	3.35 x 10 ⁴
70	y=10.471 – 12756x	106	3.53 x 10 ⁴
71	y=10.612 – 12942x	108	4.06 x 10 ⁴
72	y=10.806 – 13195x	110	4.93 x 10 ⁴
73	y= 11.061 – 13522x	112	6.36 x 10 ⁴
74	y= 11.379 – 13926x	116	8.75 x 10 ⁴
75	y= 11.765 – 14412x	120	12.9 x 10 ⁴
76	y=12.225 – 14987x	125	20.4 x 10 ⁴
77	y=12.798 – 15695x	131	36.1 x 10 ⁴
78	y= 13.651 – 16724x	139	84.8 x 10 ⁴
79	y= 16.035 – 19516x	162	92.0 x 10 ⁵
80	y= 14.889 – 18220x	152	29.3 x 10 ⁵

639 Note: When the conversion was calculated, using the equations presented in this table,
 640 the match was within ± 5% of the experimental data obtained.

641

642

643 **Table 3.** Apparent activation energies and pre-exponential factors (Uniform-Reaction
 644 Model).

Carbon conversion (%)	Arrhenius equation $\ln(k) = \ln(A) - \frac{E}{R_g} \frac{1}{T}$	Apparent activation energy, E (kJ mol ⁻¹)	Pre-exponential factor, A (bar ⁻ⁿ s ⁻¹)
10	y=9.3771 – 11620x	96.6	1.18 x 10 ⁴
20	y=9.6351 – 11697x	97.2	1.53 x 10 ⁴
30	y= 9.684 – 11768x	97.8	1.61 x 10 ⁴
40	y= 10.075 – 12182x	101	2.37 x 10 ⁴
50	y=10.555 – 12598x	105	3.84 x 10 ⁴
60	y=10.725 – 12644x	105	4.55 x 10 ⁴
70	y=10.873 – 12756x	106	5.27 x 10 ⁴
71	y=11.023 – 12941x	108	6.13 x 10 ⁴
72	y=11.231 – 13195x	110	7.54 x 10 ⁴
73	y= 11.498 – 13522x	112	9.85 x 10 ⁴
74	y= 11.828 – 13926x	116	13.7 x 10 ⁴
75	y= 12.227 – 14412x	120	20.4 x 10 ⁴
76	y=12.7 – 14987x	125	32.8 x 10 ⁴
77	y=13.228 – 15695x	131	59.0 x 10 ⁴
78	y= 14.155 – 16723x	139	14.0 x 10 ⁵
79	y= 16.525 – 19482x	162	15.0 x 10 ⁶
80	y=15.426 – 18220x	152	50.1 x 10 ⁵

645 Note: When the conversion was calculated, using the equations presented in this table,
 646 the match was within $\pm 5\%$ of the experimental data obtained.