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23 the average luminous intensity during the volatile combustion process of pine and eucalyptus
24 particles, which, according to literature, could not be observed by optical pyrometry. The observed
25 peaks correspond to the devolatilisation of hemicellulose and cellulose. The ratio between the
26 estimated char burnout time and volatile combustion time increases quadratically with the fixed
27 carbon to volatile matter mass ratio, confirming char combustion is much slower than volatile
28 combustion.

29

30 **Key words:** single biomass particle; combustion; visual drop-tube furnace; luminous intensity;
31 flame imaging

32

33 **1. Introduction**

34 In recent decades, nations around the world have attached more importance to renewable energy
35 resources such as biomass, taking them as a crucial part of the energy mix. In addition to various
36 woody feedstock, biomass fuels also include all kinds of agricultural and forestry wastes, such as
37 straw, sawdust, rice husks, peanut shells, bagasse, and animal waste as well as organic municipal
38 solid waste. They are mainly composed of carbon, hydrogen, oxygen, nitrogen and other elements.
39 Usually with high volatile matter content, high carbon reactivity, low nitrogen and sulphur contents
40 and low ash content, biomass has a very short production/replantation cycle of a few years and
41 hence is an ideal carbon-neutral replacement fuel for coal. However, biomass differs from coal in
42 many aspects in terms of fuel properties and hence combustion behaviours. In addition, some
43 properties such as moisture, volatile matter, ash and alkali metal contents can significantly affect
44 biomass combustion processes in terms of flame stability and combustion efficiency, and cause
45 various operational problems such as fouling, slagging and corrosion of heat exchange tubes within
46 the pulverised-fuel combustion boilers [1]. To understand the underlying causes of these problems,

47 a profound understanding of the combustion characteristics and combustion kinetics of various
48 biomass fuels is crucial.

49

50 Due to the prominent status in power generation, pulverized coal combustion has been the
51 research focus for past several decades. Numerous scientific publications have been assembled
52 detailing the ignition and combustion behaviours of individual coal particles [2-11]. The commonly
53 used techniques include thermogravimetric analysis (TGA) [9], optical pyrometry [2-10], high-speed
54 cinematography [2-6, 9], modelling [7, 11] and sometimes in conjunction with morphological
55 examinations [2, 5, 9]. Over recent years, a number of studies on biomass particle ignition and
56 combustion characteristics have sprung up, using the similar experimental setup and techniques to
57 the coal particles [10, 12-25].

58

59 Toptas et al. [13] investigated the combustion behaviour of different kinds of torrefied biomass
60 (lignocellulosic and animal wastes) and their blends with lignite via a non-isothermal TGA method in
61 air. It was found that the ignition and burnout temperatures were reduced by blending biomass
62 into the coal. Liu et al. [14] evaluated the combustion performance of one herbaceous biomass
63 (corn cob), one woody biomass (hardwood) and one bituminous coal using TGA and differential
64 thermal gravity (DTG) analysis. The investigation focused on the influence of heating rates, blending
65 ratios and sample kinds on the combustion behaviours and kinetics. Wei et al. [15] also investigated
66 the combustion behaviours of anthracite coal/spent coffee grounds under oxy-fuel conditions by
67 TGA and DTG analysis.

68

69 Levendis et al. [10] developed a three-colour ratio pyrometer to measure the surface temperatures
70 and high-temperature combustion rates of burning carbonaceous particles. They also compared the

71 features and performance of this instrument to those of a two-colour ratio pyrometer reported
72 earlier [26]. The three-colour ratio pyrometer was also used in their other investigations on the
73 ignition and combustion characteristics of coal particles [2-5]. Riaza et al. [12] investigated the
74 combustion behaviours of four kinds of pulverized biomass samples (sugarcane bagasse, pine
75 sawdust, torrefied pine sawdust and olive residue) in a drop-tube furnace, at 1400K, under both air
76 and oxygen-enriched combustion conditions using the three-colour pyrometry method. The
77 obtained temperature-time profiles of the burning particles were used to deduce the char
78 combustion temperatures.

79

80 Comparing to the conventional TGA and optical pyrometry, high-speed cinematography offers a
81 temporal and spatial means for the visualisation and non-intrusive measurement of a high dynamic
82 process such as particle combustion, and consequently the quantitative characterisation of the
83 burning particle, including particle size, shape, ignition, etc. Riaza et al. [12] used a high-speed video
84 camera, at a frame rate of 1000 or 2000 fps (frames per second), fitted with an infinity model K2
85 long-distance microscope lens to provide high-magnification images of the combustion events. The
86 behaviours of the four types of biomass samples were found to be similar with two phases: the
87 initial volatile flames and the consequential char combustion. Mason et al. [22] used a FujiFilm
88 Finepix HS10 camera for video recording, with a frame rate of 120 fps, and evaluated the ignition
89 delay, volatile burning time and char burnout time based on the images captured. Carlsson et al.
90 [23] captured the behaviour of biomass particles (European spruce and American hardwood) during
91 pyrolytic reactions by means of high-speed imaging and image processing to track the contour of
92 the biomass particles. Gao et al. [24] proposed a novel instrumentation system, incorporating a
93 colour CCD camera and multi-wavelength laser sources, to achieve the on-line continuous
94 measurement of particle size and shape distributions. In contrast to the single-laser technique, this

95 system was statistically more representative and more reliable. Qian et al. [25] presented the on-
96 line continuous measurement of mean particle velocity, concentration and particle size distribution
97 of pulverized fuel using multi-channel electrostatic sensing and digital imaging techniques.
98 However, most of the previous studies using high-speed cinematography focus on the
99 measurement of particle size, shape, ignition delay, combustion duration time etc. and few, if any,
100 have investigated the luminous intensity of the flame, which may bring new knowledge on the
101 understanding of the biomass particle combustion process. In addition, as recently pointed out by
102 Wang et al. [27], a proper image enhancement technique is essential to the understanding of
103 combustion flames recorded by a high-speed camera.

104

105 In present work, high-speed cinematography was used as the main methodology to study the
106 biomass combustion behaviours of both volatile matter and char residue. From the obtained
107 images, the profiles of equivalent flame diameter and average luminous intensity were deduced by
108 means of image processing, which represents a new attempt to derive some of the biomass
109 combustion characteristics as few have done it so far. The combustion durations of volatile matter
110 and char residue were also calculated and analysed.

111

112 **2. Biomass fuel characteristics and experimental methods**

113 **2.1 Physical and chemical properties of the biomass fuel particles**

114 Three different types of biomass fuels were studied: pine pellets, olive residue and eucalyptus
115 pellets. Pine pellets were made from 100% pine sawdust by-product from saw-mills with the timber
116 coming from various sustainable UK forests. The Olive residue with a particle size of less than 1mm
117 was the olive oil by-product. It was a bio-fuel of choice for co-firing in some UK power stations, due
118 to its low cost and the high security of supply. Eucalyptus pellets were obtained from a UK power

119 station which was co-firing the pellets with coal. All the biomass fuels were further ground to less
120 than 212 μm using a Retsch planetary ball mill (PM 100) and sieved to different size ranges. The size
121 cut of 125-150 μm was selected for the experiments on the consideration of problem-free and
122 stable feeding. Proximate analysis of the biomass fuels was carried out according to the current
123 British/European Standards (EN ISO 16948, EN ISO 18122, EN ISO 18123, EN ISO 18134); in
124 particular, the volatile matter was determined at 1173 K and the ash content at 823 K. The
125 elemental compositions (C, H, N, S) of the fuel samples were determined using a Thermo Flash EA
126 1112 Series, whereas the high heating values of the biomass fuels were calculated using the
127 correlation developed by Friedl et al. [28]. Table 1 shows the proximate and ultimate analysis as
128 well as the high heating values of the tested biomass fuels.

129

130

(Table 1)

131

132 **2.2 Experimental setup**

133 2.2.1 Visual Drop-tube furnace (V-DTF)

134 A visual drop-tube furnace was used for the combustion experiments with the schematic of the
135 experimental setup shown in Fig.1. The furnace was a lab-scale entrained-flow reactor fitted with a
136 1400 mm long quartz-tube, of which 1000 mm was electrically heated, with an inner diameter of
137 50mm. There was a slotted side window (30 mmx560 mm), positioned at the mid-section of the
138 furnace, through which the high-speed cinematography could be conducted. A water-cooled
139 feeding probe (internal diameter of 5 mm and length of 760 mm) and a water-cooled collection
140 probe (internal diameter of 15 mm and length of 610 mm), both made of 316 stainless steel, were
141 positioned axially at the top and bottom of the quartz tube. The separation distance between the
142 two probes can be changed but was fixed at 530 mm for the experiments reported in this paper.

143 For the individual particle combustion tests, a small amount (a few milligrams) of each fuel sample
144 was manually dropped to the furnace through the water-cooled feeding probe without the use of a
145 carrier gas but with the supply of the secondary air at 5 L min^{-1} (Fig.1). The furnace temperature
146 was set at 1073 K and the reactor temperature (measured by a type-R platinum thermocouple
147 enclosed in a high purity alumina protection tube) between the two probes was about 1058 K with
148 a variation of less than 5 K.

149

150 **(Figure 1)**

151

152 2.2.2 High-speed camera

153 A high-speed camera (Phantomv12.1) was used to study the burning of single biomass particles.
154 The camera is capable of recording videos at a frame rate up to 1,000,000 fps. At its full resolution
155 (1280 x 800 widescreen), it can shoot at a frame rate of 6,242 fps. The camera was fitted with a
156 long distance microscope lens (Questar QM-1), ranging from 56 cm to 152 cm with a resolution of
157 $1.1 \mu\text{m}$ at 15 cm, to provide high-magnification images of combustion events. The camera was
158 positioned adjacent to the slotted window, with the frame rate of 6,200 fps throughout the
159 experiments.

160

161 Multiple runs of combustion experiments were conducted for each biomass fuel, where some video
162 recordings were discarded due to various reasons such as problematic feeding and blurred
163 recording. From the reserved videos, a minimum of 20 individual burning particles for each fuel,
164 which had the entire combustion process recorded in the video, were selected and analysed in this
165 work as to be described below.

166

167 **3. Results and Discussion**

168 **3.1 Observations on combustion behaviour**

169 A set of snapshot photographic sequences of typical combustion events in air for each biomass
170 sample during burning history are shown in Fig. 2. In order to display the whole combustion process
171 more clearly, image enhancement was performed on all images in Fig. 2. The image enhancement
172 here is the adjustment of grey-scale, which maps the intensity values in grey-scale image to new
173 values. This increases the contrast of the output image in order to help us observe the combustion
174 process more clearly. However, it should be noted the image enhancement was only used in Fig. 2
175 but not in the calculations of other figures.

176

177 **(Figure 2)**

178

179 **3.1.1 Eucalyptus**

180 The eucalyptus particles consistently experienced two separate combustion stages. That is, the vast
181 majority of the char residues ignited almost simultaneously (within the interval of less than one
182 millisecond) when the volatile flames extinguished, see Fig.2 (a). Upon a particle being heated up in
183 the V-DTF, the volatile matter ignited, forming a faint (hardly detectable) envelope flame around
184 the particle. Such flames had strikingly spherical shapes, with an increasing luminosity from the
185 centre to edge. As the devolatilisation progressed, the luminosity of the flame enhanced, whereas
186 the size of the particle shrank gradually. Then, the particle accelerated its rotation suddenly and the
187 volatile flame extinguished a couple of milliseconds later. Upon the extinction of the volatile flame,
188 the ignition of char occurred. The solid char combustion event had a much higher intensity than the
189 volatile flame, which was seen from the brightly burning particle. The radiation intensity remained
190 relatively constant with time, but eventually, decreased quickly. During the solid char combustion

191 stage, a number of eucalyptus particles fragmented to several parts and the fragments continued
192 burning until completion.

193

194 3.1.2 Pine

195 The pine particles had similar combustion behaviour with eucalyptus particles, in terms of gas-
196 phase combustion and solid char combustion, as displayed in Fig.2 (b). The volatile envelope flames
197 were distinct and easily discernible from the background. Such flames occurred for a relatively long
198 duration, with the flame size decreasing during the second half of the gas combustion. Suddenly
199 occurred fast rotations of the burning particle were also observed before extinction of the volatile
200 flame. After the ignition of char residue, the burning particle became increasingly luminous and the
201 flame contour became greater along with the extension of the burning surface. Then the flame
202 remained stable in size with high intensity. Afterwards, fragmentations took place for most pine
203 particles.

204

205 3.1.3 Olive

206 The olive particles also exhibited two-phase combustions, however, somewhat differently as shown
207 in Fig.2 (c). Firstly, when the volatile matter was burning, the flame was much fainter than the
208 volatile flames of other two types of biomass fuels and without the notable spherical envelope.
209 Upon the extinction of the volatile flame, the char particle experienced a brief ignition delay period,
210 appearing to be dark for about one millisecond. Then the char ignition occurred at a corner of the
211 particle and spread gradually across the whole surface, with an increased luminosity. A similar
212 conclusion was found by Levendis et al. [29] that the char particles do not ignite over their whole
213 external surface, but exhibit preferential ignition at specific sites. After a period of steady and fast
214 burning, the shrinking core faded away.

215

216 The three types of biomass particles shared the behaviour of two evident combustion phases, the
217 volatile combustion in a spherical and low-luminous envelope flame and the high-intensity char
218 residue combustion. The olive residue had a fainter volatile flame than pine and eucalyptus due to
219 its high ash content. During the char combustion phase, fragmentation took place for all three
220 types of biomass particles but more often for pine particles. Some of the combustion characteristics
221 of biomass particles seen in this study were also observed by other researchers [2, 12], including
222 the sequential particle devolatilisation with ignition and burning of the volatiles around the particle,
223 followed by the ignition, combustion and extinction of the char residue.

224

225 **3.2 Flame contour**

226 For each combustion event, a group of frames from the high-speed video were imported to Matlab.
227 Otsu's method [30] was used to convert a grey-level image to a binary image by calculating the
228 optimum threshold.

229

230 Fig.3 shows the typical profiles of flame contours during their entire burning history, deduced using
231 image processing. Since both the volatile flame and burning char were irregularly shaped, the
232 contour area can generally be represented in terms of an equivalent diameter. This was achieved
233 by transforming the contour area to its equivalent circle which has the same number of pixels of
234 the contour area. The equivalent diameter was then defined as the diameter of the equivalent
235 circle.

236

237

(Figure 3)

238

239 The profiles of the flame equivalent diameter shown in Fig.3 indicate that the three kinds of
240 biomass particles were all burning in two distinct phases, one with a relatively large volatile
241 combustion flame and the other with a small luminous burning char body, agreeing with the visual
242 observations described in Section 3.1. Fig.3 also illustrates that, for pine and eucalyptus particles,
243 the diameter of the volatile matter combustion flame (60 pixels) was about twice as large as that of
244 the char body (30 pixels). Olive extended the disparity in the equivalent diameter to about five
245 times. A similar trend was found by Khatami et al. [31] who had tested three types of biomass
246 particles (bagasse, pine sawdust and olive residue) within the range of 75-150 μm and found the
247 peak size of the envelope flame was around 190-300 μm . For all three kinds of biomass particles,
248 the flame size decreased slowly during most of the char combustion stage and then experienced a
249 dramatic decline shortly before the final burn-off, which indicates shrinking core combustion
250 behaviour. Previous work by Levendis et al. [2] and Khatami et al. [4] reported that sugarcane
251 bagasse particles also exhibited a shrinking core behaviour during the char combustion stage.

252

253 **3.3 Average luminous intensity**

254 The profiles of the average luminous intensity during the entire combustion process of each biomass
255 fuel were also deduced by analysing the recorded images frame by frame as shown in Fig.4. The
256 luminous intensity values were expressed by the mean grey values of all pixels within the flame
257 contours.

258

259

(Figure 4)

260

261 For all fuels, the char combustion phases were easily identified by the conspicuously large values of
262 the average luminous intensity. In all cases, the char combustion phases were much more

263 luminous. For pine and olive particles, the average luminous intensity could reach the peak value
264 of almost 100 in grey value but for the eucalyptus particles, it could only reach about 70. The
265 aforementioned phenomenon that the olive volatile matter burning with a quite fainter (with a
266 value of no more than 10) flame than the other two biomass fuels (with a value of more than 20)
267 could also be noticed on the luminous intensity profiles (Fig.4). These indicate that the eucalyptus
268 particles burned at a lower temperature than pine and olive particles under the same V-DTF setup
269 conditions (at 1073 K furnace temperature and in air) despite the fact that eucalyptus has the
270 highest volatile matter content. The rapid release of the larger cloud of volatiles with the
271 eucalyptus particles may have retarded the diffusion of O₂ and hence lead to lower combustion
272 temperatures at both the volatile and char combustion stages.

273

274 It is worth noting that there are two peak values in both the equivalent diameter (Fig.3) and the
275 average luminous intensity (Fig.4) during the devolatilisation/volatile combustion stages of the pine
276 and eucalyptus particles, which were not observed by means of optical pyrometry according to a
277 previous study [12]. Riaza et al. [12] investigated the combustion of single particles of four kinds of
278 biomasses (sugarcane bagasse, pine sawdust, torrefied pine sawdust and olive residue) by use of a
279 drop-tube furnace and three-colour pyrometry. They found that the first three types of biomass
280 particles only had one pyrometric peak during the volatiles combustion stage. In addition, the
281 pyrometric peak of the olive's volatiles combustion was found to be much weaker than that of
282 other biomass samples. Some analogous but not quite equivalent observations of the two peaks
283 shown in Figs. 3-4 could be found with thermogravimetric analysis as shown in Fig.5. The same
284 biomass fuels were combusted in air in a TGA at a ramp rate of 3 K min⁻¹ to elucidate the
285 temperatures at which changes in fuel mass occurred. All of the biomass fuels were found to have
286 multiple peaks in the burnout analysis. Furthermore, during the devolatilisation stage, the olive

287 residue and eucalyptus gave two clear peaks relating to the expected devolatilisation of
288 hemicellulose and cellulose [32]. For the pine particles, the other volatile peak, not detectable, was
289 assumed to be subsumed by the main peak (Fig. 5), which may be confirmed by the much smaller
290 value of the first peak than the second one in Fig.4 (b). Therefore, the observed two peaks of the
291 eucalyptus and pine particles during the volatile combustion stage (Figs. 3-4) in V-DTF also likely
292 indicated the devolatilisation of hemicellulose and cellulose. The expected two peaks of the olive
293 particles could not be observed due to the extremely faint volatile flame as mentioned in Section
294 3.1.3.

295

296 **(Figure 5)**

297

298 **3.4 Volatile combustion time and char burnout time**

299 The volatile combustion time and the char burnout time were estimated from both of the
300 cinematographic observations (in Section 3.1) and the profiles of luminous intensity (in Section 3.3).
301 The mean values and standard deviations for all cases were calculated, from a minimum of 20
302 samples for each fuel. It was found that the combustion time of each particle varied considerably
303 because of different sizes and shapes, although they were ground and sieved to 125-150 μm . To
304 ensure that the particle sizes are basically identical, a small number of the particles with the volatile
305 combustion time and the char burnout time far beyond the standard deviations were removed
306 from the data set. Then the final average values and standard deviations were recalculated and
307 shown in Table 2.

308

309 **(Table 2)**

310

311 Fig.6 gives the total number of burning particles finally used for the analysis shown in Table 2. It can
312 be seen from Fig. 6 that there was a little correlation between the volatile combustion time and the
313 char burnout time for any of the three biomass fuels.

314

315

(Figure 6)

316

317 Intuitively one would expect that the volatile combustion time would increase with the volatile
318 matter content of the fuel and the char burnout time would increase with the fixed carbon content
319 of the fuel. Contrary to this expectation, the volatile combustion time shown in Fig.7 decreased
320 slightly with the volatile matter content. There are a number of possible reasons for this
321 observation. Firstly, the determination of the precise initial instance of the volatile ignition was
322 difficult because of the low luminosity of the volatile envelope flame thus low contrast with the
323 background. Secondly, the process of the visible volatile combustion did not cover the entire period
324 of the devolatilisation that should start much earlier than the volatile flame becoming visible.
325 Thirdly, the olive residue has a much higher ash content than the other two fuels, which may
326 influence the combustion behaviour of the volatile matter. Riaza et al. [12] also pointed out that
327 the olive residue had a lower temperature and less-influenced char burnout time compared to
328 other biomass fuels because of its high ash content.

329

330

(Figure 7)

331

332 Fig. 8 shows the relationship between the char burnout time and the fixed carbon content of the
333 fuels. It shows clearly that the char burnout time increases with the fixed carbon content of the fuel
334 as expected and agrees with the findings of Riaza et al. [5]. The olive residue has the highest fixed

335 carbon content and thus exhibited the longest char combustion time, whereas eucalyptus had a
336 fixed carbon content of about half of that of the olive residue and pine, and exhibited a much
337 shorter char burnout time.

338

339

(Figure 8)

340

341 Although the three biomass fuels were ground and sieved to the size cut of 125-150 μm , the
342 particles can differ not only in sizes but also in shapes which could be spherical, cylindrical or even
343 needle-shaped. The sizes and shapes of the particles would certainly have influenced the
344 combustion characteristics of the fuels, particularly the durations of volatile combustion and char
345 burnout. To minimize the influence of the particle size and shapes on the observed combustion of
346 volatiles and char, the ratio between the char burnout time and the volatile combustion time, was
347 used for further analysis in this study. Fig. 9 shows clearly that the ratio between the char burnout
348 time and the volatile combustion time was well correlated with the fixed carbon to volatile matter
349 mass ratio . This confirms that the char combustion is a much slower process than the volatile
350 combustion process. Fig. 9 also agrees with Riaza et al.[5] who found the dependency of char
351 burnout times versus the fixed carbon content was quadratic for air and lower oxygen mole
352 fractions in CO_2 (21% O_2).

353

354

(Figure 9)

355

356 **4. Conclusions**

357 This research has demonstrated that the combination of the visual drop tube furnace and the high-
358 speed cinematography with image processing can be an excellent tool to study the combustion

359 characteristics of individual pulverised biomass particles. All three kinds of biomass samples (pine,
360 olive and eucalyptus) have shown two burning phases consisting of the enveloped faint volatile
361 combustion phase and the bright, relatively stable char combustion phase. The two peak values in
362 the profiles of the flame size and the average luminous intensity during the volatile combustion
363 process of pine and eucalyptus particles appear to correspond to the devolatilisation of
364 hemicellulose and cellulose, and this represents new insight to the understanding of the volatile
365 combustion process of biomass. Furthermore, the ratio between the estimated char burnout time
366 and volatile combustion time increases quadratically with the fixed carbon to volatile matter mass
367 ratio, confirming that the char combustion is a much slower process than the volatile combustion
368 process.

369

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