

Time-resolved temperature measurements for inert and reactive particles in explosive atmospheres

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Abstract

The current study extends the understanding of the dynamics of the ignition process of fuel-air mixtures caused by laser-irradiated particles via the quantification of the particle heating process. Temperature measurements have been conducted under different irradiance in order to investigate the relationship between the absorption-emission properties of inert and reactive particles using emission spectroscopy. Temporal temperature information has been obtained at different boundary conditions for a range of carbon based powders including carbon blacks and graphites, as well as silicon carbide powders of different sizes. The particle size was found to have a significant impact on the heating process. Specifically, finer particles led to enhanced heating rates due to the reduced mass and thermal capacity, and the rate increase with irradiance for both inert and reactive particles was also quantified. The particle surface temperatures necessary to cause ignition of a surrounding charge were obtained and two different ignition regimes were observed. For non-reactive particles, the surface temperature plays the ma-

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major role and for silicon carbide particles the ignition temperature was found to be 1200 ± 200 K. By contrast, results obtained with reactive powders that feature similar times to ignition suggest that the temperature is not the only ignition criterion.

Keywords: Radiation-ignition, Vapour cloud explosions, Carbon black, Emission Spectroscopy

Colloquium: Detonation, Explosions and Supersonic Combustion

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Table 1: 155 (method 2)

Figure 1: 155 (method 2)

Figure 2: 155 (method 2)

Figure 3: 155 (method 2)

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Figure 5: 155 (method 2)

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Figure 9: 220 (method 2)

1. Introduction

Loose powders of fine particles can cause ignition of a surrounding fuel-air mixture when heated rapidly by radiation from an infrared laser source [1]. In vapour cloud explosions, fine particles, raised by the expansion of the combustion products, can be exposed to high heat loads due to the forward thermal radiation with infrared characteristics emanating from the hot product cloud. Ignition ahead of the main flame front may be induced with radiation levels similar to those measured in large scale hydrocarbon fires [1]. Likewise, fibrous targets that exhibit high absorption in the far-infrared (FIR), while their volumetric heat capacity is maintained at similar levels to that of the adjacent fuel-air mixture, can also cause ignition [2, 3, 4].

Radiative ignition is also of potential importance for the assessment of ignition hazards arising from the use of optical fibres in flammable atmospheres. Light emanating from faulty fibre optic systems can heat particle(s) causing an accidental ignition. Hills et al. [5] and Zhang et al. [6] showed that for ignition of hydrogen-air mixtures by a single coal particle held at the fibre tip, the ignition process was controlled by the incident laser power, while Adler et al. [7] showed that ignition by fibrous mats irradiated using large beam cross-sections is determined by the incident power flux. Carleton and Weinberg [8], reported that this relates to the minimum ignition energy of the mixture which varies linearly with the time and area.

Whilst the necessary incident power or flux required to cause ignition are relatively well documented, little is known about the particle surface temperatures and, in particular, their temporal evolution. Stamatov et al. [9] suggest that temperatures of at least 950 K are necessary for ignition of a

26 stoichiometric methane-air mixture by radiatively heated inert particles with
27 a size of 320 - 480 μm , while calculations carried out by Hills et al. [5], for
28 ignition of a lean hydrogen-air mixture by an irradiated coal particle, suggest
29 a particle surface temperature of 800 K. Adler et al. [7] suggest temperatures
30 of 928 K and 950 K for ignition of stoichiometric propane- and methane-air
31 mixtures by a silicon carbide coated Kaowool mat (inert insulation wool)
32 irradiated by 1064 nm light. Similarly, for spheres made of plain Kaowool
33 fibres irradiated by FIR light, the corresponding temperatures were 922 K
34 and 1022 K for the same mixtures.

35 Beyrau et al. [1] examined a unique system featuring sub-micron particles
36 irradiated over comparatively large areas in ignitable butane-air mixtures.
37 The experimental study featured fine powders with very different character-
38 istics (type, size, morphology, etc.) and the ignition times scales were found
39 to decrease with increasing irradiance. A commercially available carbon black
40 powder (acetylene black) coated on a glass substrate was found to give rise to
41 short ignition time scales ($\simeq 100$ ms) in a stoichiometric butane-air mixture
42 using an irradiance < 600 kW/m². Due to the high spectral absorptivity in
43 the infrared, the enhanced heat transfer to adjacent gas due to the nanos-
44 tructure particle surface and, possibly, the favourable chemical reactivity,
45 carbon black powders produced very short ignition times. However, there is
46 little further knowledge on the heating behaviour of these powders and, more
47 importantly on the particle surface temperatures necessary to cause ignition
48 of an adjacent flammable mixture.

49 Apart from the fundamental interest to combustion science, it is expected
50 that the simultaneous characterisation of ignition events in terms of surface

51 temperature in addition to the established times to ignition [1] will enable a
52 multi-parameter (e.g., temperature and time to ignition) validation of future
53 calculation methods aimed at representing this novel ignition mechanism
54 and thereby support the development of improved tools for the quantitative
55 assessment of explosion hazards. The objective of the current study is hence
56 to extend the understanding of the dynamics of the ignition process under
57 idealised conditions (e.g., no attenuation from the particles and maximum
58 absorption) that can be considered a worst case scenario for a practical event.
59 The relationship between absorption-emission properties of different powders
60 is investigated further by the determination of particle temperatures under
61 different irradiance using emission spectroscopy (ES) [10]. The materials
62 used (e.g., carbon black, graphite, silicon carbide) feature relatively well
63 defined emissivities and, hence, particle thermometry is used to obtain useful
64 information on the ignition mechanism. Finally, results from the study by
65 Beyrau et al. [1] suggest that the chemical reactivity of carbon black powders
66 may influence the ignition process; this hypothesis is examined on the basis
67 of determined particle temperatures.

68 The present study extends previous efforts by systematic investigations
69 into the heating behaviour of different powders at different boundary con-
70 ditions. (i) Steady state temperatures are established as a function of the
71 incident irradiance. (ii) Temporal temperature information is obtained for
72 both inert and reactive particles. (iii) The influence of the powder particle
73 size on the corresponding heating behaviour is explored under constant ir-
74 radiance and (iv) the surface temperatures necessary to cause ignition are
75 determined for both reactive and inert particles.

76 2. Experimental method

77 A stainless steel flame tube of 90 x 60 mm rectangular cross-section and
78 240 mm length was used [1]. The chamber was equipped with a fused silica
79 window (115 × 60 mm) which allowed the simultaneous illumination of the
80 selected targets and the use of optical diagnostics techniques. The desired
81 equivalence ratio (ϕ) was obtained using the method of partial pressures via
82 a pressure transducer (KIMO MP 105 E) with a reading accuracy of 0.5 %.
83 For a stoichiometric butane-air mixture the resulting overall accuracy was
84 $\phi = 1.0 \pm 0.02$. The reactants were fed into the tube via the dedicated lines
85 shown in Fig. 1. Mixture homogeneity was achieved after circulating the
86 reactants for 70 **flow-through** times in a closed loop. The open end of the
87 tube was sealed using a thin aluminium foil that ruptured due to the pressure
88 rise following ignition [1].

89 Candidate particulates were placed at the centre of the flame tube and il-
90 luminated by a near-infrared (NIR) continuous wave laser diode (808 ± 2 nm,
91 50 W). Full lasing could be achieved within 2 ms given a pre-determined tar-
92 get power, thus enabling a sufficiently precise definition of the illumination
93 time. The laser power was measured for each experiment via an on-board
94 monitor diode. The spatial distribution of laser power was determined using
95 a CCD camera. The beam size was considered as 68 % (1/e) of the Gaus-
96 sian laser profile; a maximum irradiance of 1.6 MW/m^2 could be applied
97 over approximately 32 mm^2 . The conditions used in the current study follow
98 Beyrau et al. [1] unless otherwise stated. Ignition times (τ_{ign}) were obtained
99 from images recorded by a CCD camera (AVT PIKE F-032 COLOR) at a
100 rate of 208 fps. The onset of ignition was regarded as the appearance of

101 visible flame in the recorded frames, while the ignition time was defined as
102 the interval from illumination to ignition corresponding to an uncertainty of
103 ± 5 ms. The reported times include the particle and gas heating times and
104 are, hence, different from conventional induction times. Once the investi-
105 gated target was positioned, the tube was sealed, the mixture produced and
106 the powder irradiated.

107 Time-resolved spectroscopic temperature measurements were performed
108 using an Ocean Optics NIRQuest 512 spectrometer (900 - 1700 nm) fitted
109 with a notch filter (808 nm) to suppress the scattered laser light. The spec-
110 trometer was triggered from the laser and collected the emitted radiation
111 from the illuminated powder via an optical fibre/collimator assembly at a
112 rate of 200 fps using an integration time of 1 ms. The spectral response of
113 the spectrometer was corrected using a calibrated light source (Ocean Optics
114 Cool Red Infrared Light Source) with a bulb colour temperature of 1500 K.
115 The produced correction curves accounted also for the chromatical errors
116 from the collimator, fibre and the notch filter. Particle temperatures were
117 obtained using ES, a non-intrusive optical diagnostic technique which has
118 been successfully used for measuring soot temperatures in flames [10]. The
119 technique is based on the analysis of the spectrally resolved emitted radiation.
120 Temperatures were obtained by fitting of the theoretical spectra according
121 to Planck's law of radiation to the experimentally determined one over a
122 spectral range of 900 - 1650 nm. More details on the method can be found
123 elsewhere [11, 12]. For the current investigation the emission coefficient (ε)
124 for all powders was assumed to be unity as discussed in Section 3.1.

125 The temperature within the irradiated spot might not be uniform due

126 to the Gaussian radial energy distribution of the heating laser beam. The
127 spectrometer collected light from an area approximately half of the irradiated
128 spot; this was achieved by overlapping the laser spot and the field of view
129 of the spectrometer using a low power target diode laser. The temperature
130 is expected to be approximately uniform in this reduced region and, hence,
131 the Gaussian beam profile is not expected to cause appreciable errors. The
132 investigated powders featured a non-uniform particle size distribution and,
133 thus, particles or the primary carbon black particles within the interrogation
134 region may feature non-identical heating rates due to differences in their ther-
135 mal inertia. The sampling technique used is non-linear and highly sensitive
136 to high temperatures since the collected signal follows the Stefan-Boltzmann
137 law of radiation and thus proportional to the fourth power of temperature.
138 Therefore, irrespective of any spatial temperature non-uniformities, a non-
139 linearly averaged peak temperature is determined within the sampled area
140 rather than a spatially averaged equivalent. The average, maximum and
141 minimum values were obtained from three measurements at each condition.
142 An illustrative figure is provided in the Supplemental material and shows the
143 spectra obtained from three tests. The temperature sensitivity is such that
144 good accuracy is maintained over the full range of current conditions.

145 The influence on the heating behaviour was examined for a range of pow-
146 ders of different chemical reactivity, spectral absorptivity and surface area
147 to volume ratio as shown in Table 1. The materials include a collection
148 of commercially available carbon blacks, a natural and a synthetic graphite
149 and chemically inert silicon carbides. Carbon blacks used in this study in-
150 cluded Alfa Aesar Acetylene Black, Evonik Printex 35 and 80, and Evonik

151 Colour Black FW1. Both graphite powders were sifted through a 45 μm
152 sieve. Silicon carbide powders, featuring a median particle size (d_{50}) from
153 0.6 to 370 μm , were considered to explore the influence of the particle size.
154 Particle size distributions for selected silicon carbide powders can be found
155 in the Supplemental material. The carbon based powders appear black at
156 optical wavelengths and exhibit high absorption at the incident laser light
157 of 808 nm. Silicon carbides appear grey and experimental data [7] suggest
158 lower absorptivity than soot. Our previous investigation [1] showed that
159 the properties of powder coatings have a much stronger impact on ignition
160 than the properties of the substrate, therefore in the current study only mi-
161 croscope coverslips and slides were used. A thin layer (a few hundred μm
162 thick), sufficient to appear optically dense (*i.e.*, a transparent glass substrate
163 became opaque), was applied. The particle type, incident irradiance, parti-
164 cle size and adjacent atmosphere were varied individually and the effect on
165 the heating behaviour of the powder was recorded.

166 **3. Results and discussion**

167 *3.1. The influence of powder absorptivity on the equilibrium temperature*

168 Initial experiments were performed to examine the accuracy of the applied
169 optical diagnostic technique. A validation test was carried out by compar-
170 ing the steady state temperature obtained with the spectroscopic technique
171 with temperatures measured simultaneously using a type R thermocouple
172 of 0.125 mm diameter. For this experiment, silicon carbide ($d_{50} = 0.6 \mu\text{m}$)
173 and acetylene black powder coated on microscope slides were used and the
174 thermocouple tip was buried in the investigated powder at the centre of the

175 irradiated area where peak temperatures occur. The method was used to
176 minimise the radiation errors in the thermocouple readings. Results are de-
177 picted in Fig. 2. The excellent agreement shows that ES is suitable for mea-
178 suring temperatures (800 – 1600 K) of current interest. Apart from being
179 non-intrusive, the optical diagnostic technique offers superior time resolution
180 (200 fps) compared to conventional thermocouple measurements. Also, the
181 assumption of a unity emission coefficient for both materials appears to be a
182 good approximation. Visually black and grey materials are usually modelled
183 with unit emissivity and deviations are expected to be modest.

184 Higher irradiance yields higher equilibrium temperatures as well as rate of
185 temperature rise; both directly relate to the time to ignition of an adjacent
186 charge. Equilibrium temperatures reached in air for a range of irradiance
187 for acetylene black and silicon carbide ($d_{50} = 19 \mu\text{m}$) are shown in Fig. 3,
188 along with data from Adler et al. [7] obtained with coated fibrous targets
189 heated by light of a comparable wavelength (1064 nm). The temperature
190 dependence on irradiance shows a similar trend for both materials. Also, it
191 is apparent that the interplay between absorption-emission properties of in-
192 dividual powders leads to differences between the equilibrium temperatures
193 achieved. Temperatures for silicon carbide and acetylene black vary from
194 1130 to 1337 K at 310 kW/m^2 and from 1752 to 1840 K at 1.6 MW/m^2 , while
195 the data from Adler et al. [7] range from 842 to 1202 K at 250 kW/m^2 for
196 silicon carbide and soot respectively. Interestingly, acetylene black tempera-
197 tures obtained with an irradiance of 310 kW/m^2 are above the approximate
198 onset of high temperature ignition (1200 K) promoted by chain branching
199 [13]. The silicon carbide particles can reach similar temperatures with an

200 irradiance of 625 kW/m^2 , while the soot coated mats [7] do so with an irra-
201 diance of 375 kW/m^2 . It should be also stated that with the acetylene black
202 and silicon carbide particles ignition of a stoichiometric butane-air mixture
203 was readily observed with these irradiance levels [1], albeit the ignition times
204 were of the order of 1 s.

205 *3.2. The influence of irradiance and target particle properties on the heating*
206 *behaviour of the powder*

207 When the irradiance increases, it can be expected that the rate of temper-
208 ature rise will also increase. The effect is quantified in Fig. 4, where results
209 for acetylene black particles on a coverslip in air are presented along with
210 the corresponding ignition times in a stoichiometric-butane air mixture (ob-
211 tained from Beyrau et al. [1]). The time resolution of the optical diagnostic
212 technique **used enables** the accurate characterisation of the initial heating
213 stages. As mentioned earlier, the measured ignition time scales in a sur-
214 rounding charge decreased with increasing irradiance, this directly relates to
215 the increased heating rates. This also applies to non-reactive particles, the
216 influence of irradiance on the heating behaviour of silicon carbide particles
217 can be seen in Fig. 5. Compared to the reactive acetylene black particles,
218 silicon carbide exhibits lower heating rates at the same irradiance. This may
219 be an effect of the lower spectral absorptivity as well as the particle surface
220 structure. Previous Scanning Electron Microscope (SEM) images have shown
221 that the morphological features of acetylene black are characterised by pri-
222 mary particles of 35 nm, clustered into structures with interstitial spaces [1].
223 This nanostructure particle surface may give rise to favourable heating char-
224 acteristics. Also the reactive nature of acetylene black may assist the particle

225 heating process. Nevertheless, the use of the non-combustible silicon carbide
226 enables the characterisation of the direct thermal ignition process. Obtain-
227 ing the precise chemical composition of reactive powders may not be trivial.
228 Hence, it is expected that knowledge of the temporal temperature evolution
229 of non-reactive particles will allow the validation of simplified models, used
230 for simulating this ignition process, that do not include surface reactions.

231 The temperature evolution of silicon carbide in air under constant irra-
232 diance was measured as a function of the powder median particle size, as is
233 shown for different silicon carbide powders in Fig. 6. The inert silicon car-
234 bide powders were specifically chosen for this investigation in order to make
235 sure that results were a function of the particle size only. It can be seen that
236 the rate of temperature rise increases with decreasing particle size. Mea-
237 surements were also carried out for a coarse grain powder ($d_{50} = 370 \mu\text{m}$).
238 However, results are not presented since temperatures higher than 1000 K
239 were only observed after 600 ms. It has been previously shown that fine
240 grain powders featured more than an order of magnitude shorter ignition
241 times than coarse particles in a stoichiometric butane-air mixture [1], this
242 directly relates to the corresponding heating behaviour. Finer particles fea-
243 ture higher surface area to volume ratio as well as lower mass and thermal
244 capacity. Hence, the high temperatures necessary for the ignition of the sur-
245 rounding charge can be reached more quickly. A temperature of 1040 K is
246 reached after 37 ms for a $0.6 \mu\text{m}$ powder, while the $58 \mu\text{m}$ powder reaches the
247 same temperature after 152 ms. Although not measured here, the equilib-
248 rium temperature reached in air is expected to be similar irrespective of the
249 particle size as it is expected that the powders feature similar absorptivity.

250 Fine particles enhance also the heat conduction to the surrounding gas phase
251 due to the larger specific surface area, which assists the reduction of ignition
252 times.

253 *3.3. Particle surface temperatures upon ignition of explosive mixtures*

254 Time-resolved temperature histories for acetylene black powders in air
255 and in stoichiometric butane-air mixtures are shown in Fig. 7. The particle
256 heating behaviour appears to be similar in a non-flammable and an explosive
257 atmosphere. Accordingly, if it is assumed that the heating behaviour in air
258 and in a fuel-air mixture does not change significantly, then the particle
259 surface temperature required for ignition may be estimated. This is achieved
260 by examining the powder temperature at the average time of ignition. This
261 is a reasonable assumption since most the explosive mixtures of practical
262 interest contain relatively small amounts of fuel and, hence, their thermal
263 conductivity is expected to be very similar to air.

264 The estimated “ignition temperatures” can be seen in Fig. 8. The hor-
265 izontal error bars correspond to the maximum and minimum temperatures
266 measured during the equivalent ignition time. Two different ignition regimes
267 can be observed, if the particle is non-reactive the ignition temperature is
268 1200 ± 200 K. For particle sizes from around 37 to 370 μm , which feature
269 an order of magnitude difference in ignition times [1], the ignition tempera-
270 tures are in a comparatively narrow band from 1290 to 1327 K. The value
271 drops to around 1180 K for particles in the range 9 to 19 μm . The vari-
272 ation of the ignition temperature as a function of powder median particle
273 size for different silicon carbide powders can be found in the Supplemental
274 material. For comparison, measurements from Adler et al. [7] suggest tem-

275 peratures of 928 K for propane and 950 K for methane for ignition by silicon
276 carbide coated on a (Kaowool) fibrous substrate, irradiated by 1064 nm light
277 in mixtures of unit stoichiometry. Moreover, Laurendeau [14] reported that
278 for thermal ignition of methane-air mixtures by a hot surface, temperatures
279 above 1273 K are required. Findings from the current study suggest that if
280 the particles are non-reactive the surface temperature plays the major role in
281 the ignition of the surrounding charge. This was indeed expected since the
282 phenomenon of ignition by radiatively heated inert particles is characterised
283 by direct thermal ignition.

284 For reactive powders, the particle surface temperature does not appear
285 to be the sole ignition criterion. The ignition temperature of acetylene black,
286 $\tau_{ign, Ace} = 20$ ms, is 1270 ± 60 K while Printex 80, $\tau_{ign, P80} = 85$ ms,
287 featured an ignition temperature of 1700 ± 50 K, at least 320 K higher.
288 These two powders exhibited ignition times below 100 ms in a stoichiometric
289 butane-air mixture. Ignition temperatures for Printex 35 were 1588 ± 70 K,
290 $\tau_{ign, P35} = 51$ ms; for Colour FW1 1652 ± 20 K, $\tau_{ign, FW1} = 38$ ms; for nat-
291 ural graphite 1385 ± 75 K, $\tau_{ign, GN} = 127$ ms; and for synthetic graphite
292 1355 ± 145 K, $\tau_{ign, GS} = 63$ ms. SEM images of the carbon black **pow-**
293 **ders** used can be found in Fig. 9 and as discussed by Beyrau et al. [1].
294 The carbon black powders examined have distinct morphological features.
295 Acetylene black is characterised by relatively large primary particles (35 nm)
296 and smaller structures with interstitial spaces, while Printex 80 by both
297 smaller primary particles size (16 nm) and structures without voids. The
298 morphological characteristics influence the reactivity of powders. The dif-
299 ferences may relate to local mixture enrichment effects due to evaporating

300 carbon near the particle surface or the chemical reactivity of individual pow-
301 ders. The measured times to ignition reported by Beyrau et al. [1] suggest
302 that the powder reactivity may influence this ignition mechanism, the large
303 variation in the ignition temperatures of reactive particles observed in the
304 current study confirms this argument. It has been reported that soot parti-
305 cles undergo structural modification upon exposure to continuous (e.g., Hu et
306 al. [15], 55 MW/m²) or pulsed laser irradiation (e.g., Vander Wal et al. [16],
307 5×10^5 MW/m²). The maximum laser irradiance used in the current study
308 is of the order of 1 MW/m² and, hence, it is not expected that such struc-
309 tural modification or laser ablation phenomena will substantially influence
310 the ignition process. Previous SEM analysis [1] has indicated that the mor-
311 phological features of acetylene black closely resembles car exhaust related
312 particles. Results presented in the current study show that this type of par-
313 ticles provides the most favourable ignition characteristics with low ignition
314 temperatures, in addition to the shortest ignition times.

315 **4. Conclusions**

316 Emission spectroscopy, a method for soot particle surface temperature
317 measurements in flames [10], has been used to determine time-resolved tem-
318 peratures of irradiated powders under radiation levels relevant to radiation
319 induced ignition in flammable atmospheres. This allowed the comprehensive
320 quantification of particle heating process for both inert and reactive par-
321 ticles. The dependence of equilibrium temperature on irradiance attained
322 in air by silicon carbide and acetylene black showed a similar trend with
323 coated fibrous targets [7]. Furthermore, the rate of temperature rise in-

324 creases with irradiance for both particle types which explains the decrease
325 in ignition times of a surrounding explosive atmosphere. Finer particles led
326 to enhanced heating rates due to the reduced mass and thermal capacity.
327 Particle surface temperatures necessary to cause ignition of a surrounding
328 charge were estimated from temperature histories obtained in air. Two dif-
329 ferent ignition regimes were observed, if the particles are non-reactive the
330 surface temperature plays the major role in the ignition of the surrounding
331 explosive mixture. For silicon carbide particles, ignition temperatures were
332 1200 ± 200 K for powders with different particle sizes. In contrast, for reac-
333 tive powders, the temperature appeared to be not the only ignition criterion
334 indicated by the different values measured with powders that feature similar
335 times to ignition. Furthermore, previous SEM analysis [1] has indicated that
336 the morphological features of acetylene black closely resembles car exhaust
337 related particles. The current study suggests that this type of particles show
338 the most favourable ignition characteristics with low ignition temperatures,
339 in addition to the shortest ignition times. In summary, the present work
340 has enabled the simultaneous characterisation of ignition events in terms of
341 surface temperature in addition to the established ignition time scales. It is
342 expected that data sets produced will enable a multi-parameter (e.g., tem-
343 perature and time to ignition) validation of calculation methods aimed at
344 representing this novel ignition mechanism and thereby support the develop-
345 ment of improved tools for the quantitative assessment of explosion hazards.

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Table 1: Powder data

Powder	Colour	Chemical Formula	Particle Size (μm)	Primary Particle Size (nm)
Acetylene Black	Black	C	-	35
Printex 35	Black	C	-	31
Printex 80	Black	C	-	16
Colour FW1	Black	C	-	-
Natural Graphite	Black	C	< 45	-
Synthetic Graphite	Black	C	< 45	-
Silicon Carbide	Grey	SiC	$d_{50} = 0.6,$ 9.3, 19, 37, 58	-

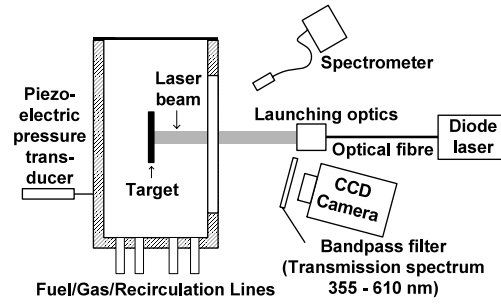


Fig. 1: Schematic of the experimental facility used for the particle thermometry.

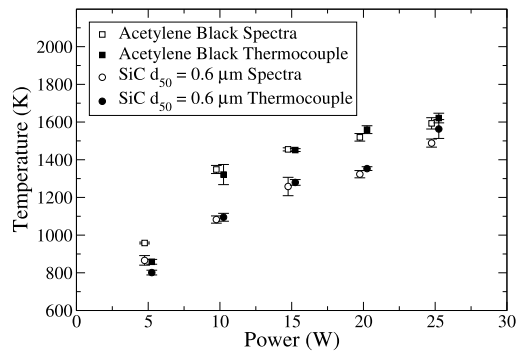


Fig. 2: Comparison of equilibrium temperature measurements of carbon black and silicon carbide on a microscope slide in air.

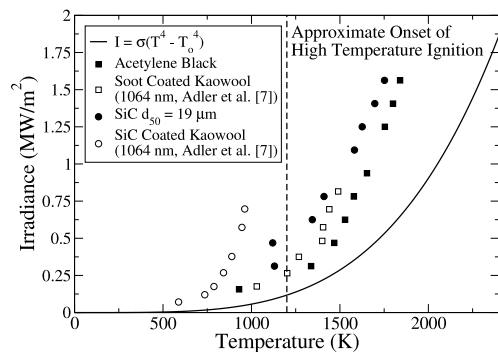


Fig. 3: Irradiance against equilibrium temperature attained in air by silicon carbide ($d_{50} = 19 \mu\text{m}$) and acetylene black on microscope coverslip. The vertical dashed line indicates the approximate onset of high temperature ignition (1200 K) promoted by chain branching [13].

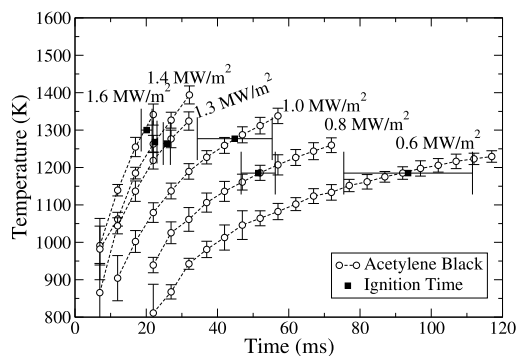


Fig. 4: Temperature histories of acetylene black on a microscope coverslip in air for different irradiance. Ignition times correspond to the average obtained in a stoichiometric butane-air mixture using the same irradiance [1].

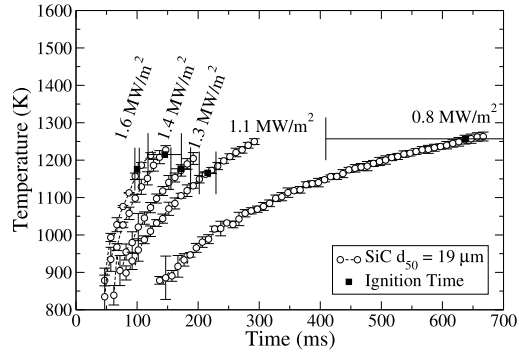


Fig. 5: Temperature histories of silicon carbide ($d_{50} = 19 \mu\text{m}$) on a microscope coverslip in air for different irradiance. Ignition times correspond to the average obtained in a stoichiometric butane-air mixture using the same irradiance [1].

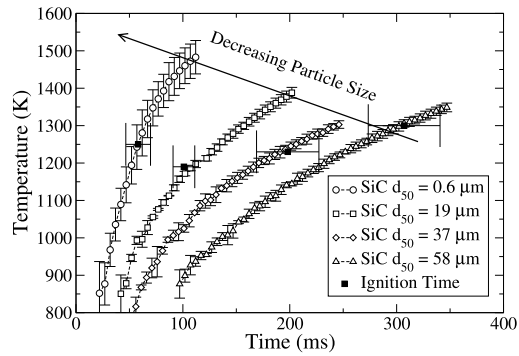


Fig. 6: Temperature histories of silicon carbide on a microscope coverslip in air for different particle sizes, irradiance = 1.6 MW/m^2 . Ignition times correspond to the average obtained in a stoichiometric butane-air mixture using the same irradiance [1].

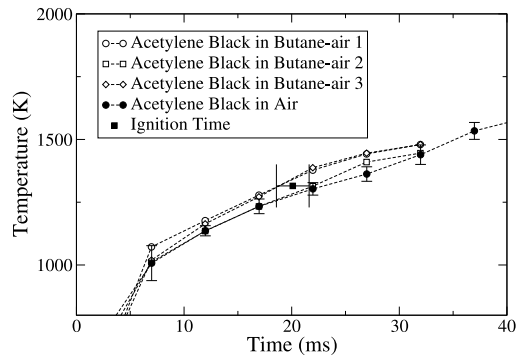


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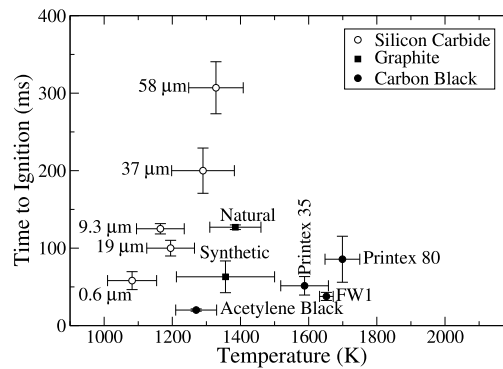


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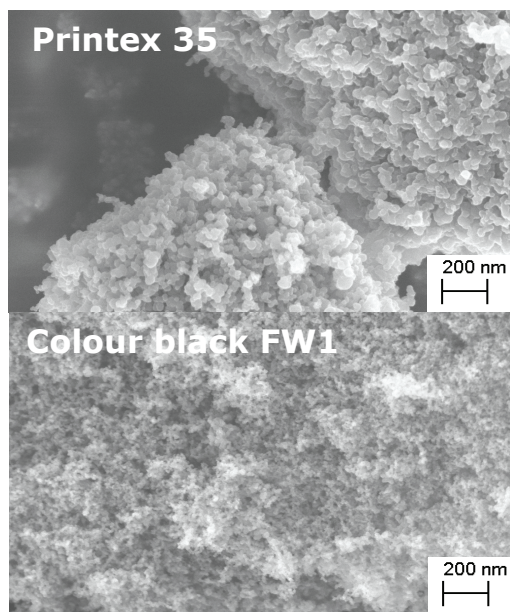


Fig. 9: SEM images of the selected carbon black powders. Ignition times in stoichiometric butane/air mixture, irradiance = 1.6 MW/m^2 : Printex 35 ($\tau_{ign} = 52 \text{ ms}$); Colour FW1 ($\tau_{ign} = 38 \text{ ms}$).

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