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Measurement of coal particle combustion behaviors in a drop tube furnace through high-speed imaging and image processing

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***Abstract*— This paper presents the measurement and characterization of single coal particles in a drop tube furnace through high speed imaging and image processing. A high speed camera coupling with a long distance microscope is employed to acquire the images of the particle during its residence time in the furnace. A set of physical quantities of the particle, including size, shape and boundary roughness, are defined and computed based on the images obtained, which are then used describe the combustion behaviors of the particle. Experimental results show that the combined high speed imaging and image processing technique has provided an effective means for measuring and quantifying the characteristics of single coal particles during combustion.**

Keywords*— *single coal particle; drop tube furnace; high speed imaging; image processing; particle combustion behaviors

I. INTRODUCTION

Solid fuels such as coal and biomass have been and will continue to be one of the major energy resources worldwide because of their abundant reserve and competitively low price. However, the properties of the solid fuels vary widely, leading to drastically different ‘fuel performance’ in a combustion process. For example, the physical profile (such as size, shape, and etc.) of fuel particles can have a great impact on their ignition and combustion behaviors, and consequently the flame stability, combustion efficiency and pollutant emissions. Experimental and modelling work has been carried out to study the ignition and combustion behaviors of single coal particles under different combustion conditions [1-4]. Levendis *et al.* and Riaza *et al.* studied the combustion behaviors of single coal particles in air where three-color pyrometry and high-speed high-resolution cinematography were used to obtain the temperature–time–size histories of the burning coal particles in a drop-tube furnace [5]. They also observed the ignition characteristics and ignition delay of the coal particles under different gas atmospheres, including replacing N_2 in air with CO_2 [6].

Whilst the characteristics of fuel particles affect the performance of the combustion system, the quantitative measurement and characterization of the fuel particles remain challenging. There are no established methods available which differentiate clearly all kinds of particle size and shape, and their variation. Carter *et al.* [7] and Qian *et al.* [8] used combined digital imaging and electrostatic sensors to obtain the size distribution and volumetric concentration of particles, which provided data for the on-line mass flow measurement of pneumatically conveyed particles. Gao *et al.* [9] incorporated a color CCD camera and multi-wavelength laser sources to achieve the on-line measurement of particle size, shape and size distributions. Quantitative information of the particles was obtained by decomposing the red, green and blue channels from the primary color images. Podcczeck [10] proposed a shape factor for the particle analysis based on two-dimensional (2-D) particle outlines through image processing. The proposed shape factor used the deviations of the 2-D particle outlines from the images of a circle, triangle and square. The particle elongation and the number of characteristic corners of the apparent shape were computed. Shaddix *et al.* [11] also analyzed the ignition and devolatilization characteristics of coal particles through imaging under different O_2/N_2 and CO_2 diluent gas conditions. Although some research was conducted in studying the size and shape of particles in pneumatic conveying pipes and furnaces, limited work has been undertaken to measure comprehensively the physical characteristics and their variation of fuel particles during the combustion.

The present study is to investigate the combustion behaviors of coal particles in the Visual Drop Tube Furnace (V-DTF) through high speed imaging and image processing. A set of characteristic parameters of the particle are defined based on the particle images obtained using a high speed camera. Image processing algorithms including contouring and closest-ellipse fitting are developed to compute the defined characteristic parameters, which are then used for profiling the combustion behaviors of the particle during its residence time in the furnace. The experimental results are presented and discussed.

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II. METHODOLOGY

A. *V-DTF and camera system*

A V-DTF is an essential facility which can provide critical data for the in-depth understanding of ignition and combustion behaviors of fuel particles in both fundamental and applied combustion research. The V-DTF used in this study is a laboratory-scale, electrically heated, entrained-flow tube furnace with a capability of combusting solid fuel particles (e.g., coal, biomass) under closely controlled conditions. Fig. 1 is the overview of the V-DTF. The combustion chamber is a 1150 mm long quartz tube with an inner diameter of 50 mm, capable of maintaining gas temperatures up to 1050°C. There is a viewing window that allows operators to visualize fuel combustion inside the tube.

One of key technical challenges in measurement of burning particles is that the size and shape of the particle vary during the residence time in the furnace. It is also known that the particles rotate significantly due to the intensive exothermic redox chemical reaction between the fuel and oxidant (e.g., atmospheric oxygen). High speed imaging is therefore essential for sensing such a variation. A high speed camera (Phantom v12.1), capable of acquiring a video at a frame rate up to 1,000,000 frames per second (fps), was employed to in the study. A long distance microscope (Questar QM-1), which has a working distance ranging from 56 cm to 152 cm with a resolution of 1.1 microns at 15 cm, was coupled with the camera to ensure that tiny particles can be captured in their residence time in the furnace.

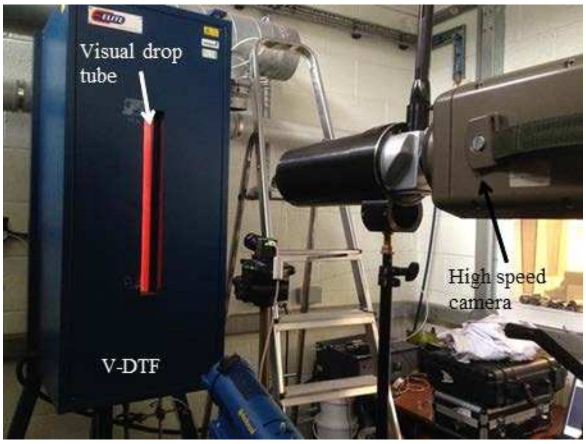


Fig. 1. Overview of the V-DTF and the camera system.

B. *Algorithms for particle characterization*

Particles are often characterized by the size, size distribution and shape factor. The particle images recorded by the high speed camera are read into a personal computer. Image progressing algorithms are then developed to process the images. A set of parameters is defined to quantify the characteristics of the particle in terms of its size, shape, boundary roughness and orientation. Fig. 2 illustrates the main steps of determining the characteristic parameters of the particle. The detailed definition and computation of those parameters are given as follows.

1) Particle contour retrieval

The particle contour retrieval is the initial step in the particle image processing. The Otsu's Thresholding method [13] was used to detect the particle contour in this study. The Otsu's method searches automatically the threshold which splits the histogram of an image into two pixel groups (i.e., foreground and background groups) and ensures that the variance of each pixel group is minimal. Once the threshold is determined, the binary format of the image can be generated so as to allow the particle contour retrieval to be performed.

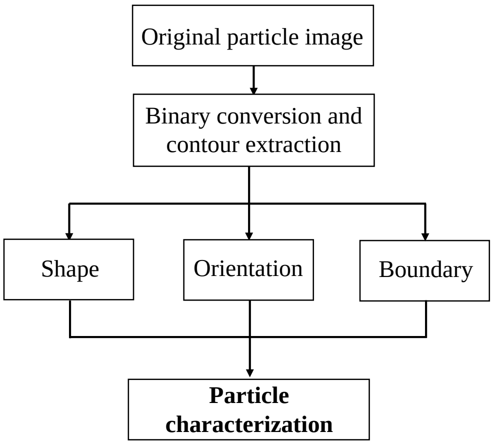


Fig. 2. Steps of determining the particle characteristic parameters.

The 8-connectivity [9] is used to extract the contour of the particle binary image. The 8-connected pixels are neighbors to every pixel that touches one of their edges or corners. Those pixels are connected horizontally, vertically, and diagonally. Let (x′, y′) and (x″, y″) be a pair of pixels in the image, the 8-connectivity can be described as,

$$\max\left(\left|x' - x''\right|,\ \left|y' - y''\right|\right) = 1\,. \qquad (1)$$

Once the contour is extracted, the characteristic parameters of the particle can be computed.

2) Shape parameters

Area- Area, *A*, is the quantity that expresses the size of the particle, which is determined by computing the number of pixels within the image contour of the particle, *R*, i.e.,

$$A = a \sum_{(i,j)\in R} 1\,, \qquad (2)$$

where *a* (mm^2/pixel) is a scale factor relating to the spatial resolution of the camera.

Circularity ratio- Circularity ratio, *Cr*, describes the similarity of a particle shape to a circle [12]. For a coal particle, the circularity ratio is the ratio of the particle area to the area of its equivalent circle (i.e., a circle which has the same perimeter as the particle, as shown in Fig. 3), and is calculated by,

$$C_r = \frac{P^2}{4\pi A}\,, \qquad (2)$$

where *A* and *P* are the area and perimeter of the particle, respectively. For a perfect circle, C_r is 1.

Eccentricity- Eccentricity, *e*, describes the shape of the particle, which can be acquired from transferring the particle to an equivalent ellipse as shown in Fig.4. The eccentricity is the ratio of the distance between the center and focus of the equivalent ellipse to its major axis length [14], i.e.,

$$e = \frac{f}{L} = \sqrt{\left|1 - \left(\frac{W}{L}\right)^2\right|}, \tag{3}$$

where *f* is the distance from the center to focus of the equivalent ellipse. *L* and *W* are the lengths of the major and minor axes, respectively. *L/W* is often regarded as the aspect ratio. For a circle, *e* is 0.

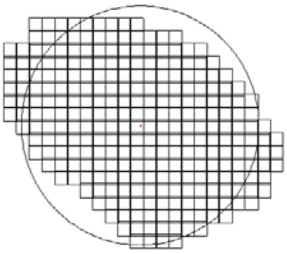


Fig. 3. A particle and its equivalent circle.

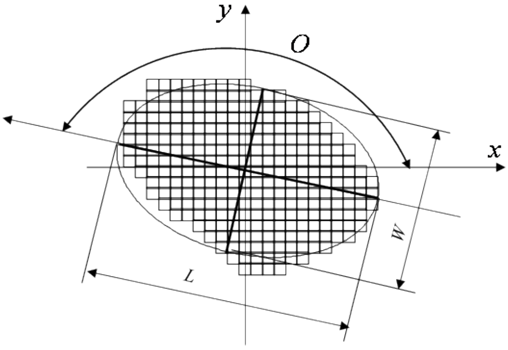


Fig. 4. A particle and its equivalent ellipse.

3) Orientation

During the combustion, fuel particles rotate rapidly due to the intensive exothermic redox chemical reaction. The orientation of the particle reflects the rotation of the particle. The orientation, *O*, can be calculated by fitting the particle to its equivalent ellipse and calculating the orientation of the ellipse as follows [15],

$$O = \frac{180^\circ}{\pi} \arctan\left(\frac{\left|\sum_{i\in S} x_i^2 - \sum_{i\in S} y_i^2\right| + \sqrt{\left|\left(\sum_{i\in S} x_i^2 - \sum_{i\in S} y_i^2\right)\right|^2 + 4\left(\sum_{i\in S} x_i y_i\right)^2}}{2\sum_{i\in S} x_i y_i} \right), \tag{4}$$

where (x_i, y_i) is the coordinate of pixel *i* within the equivalent ellipse, *S*, The orientation is counted as the angle between the major axis and the x-axis, ranging from 0° to 360°.

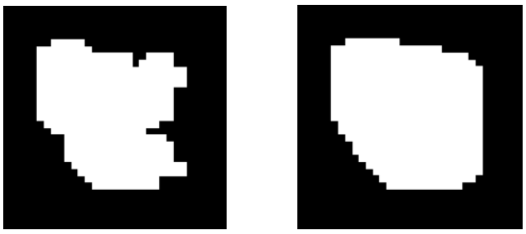
4. Boundary analysis

The profile of particle boundary reflects the changes of the particle size, shape and roughness. The following parameters are computed for profiling the particle boundary.

Boundary distance- It is the distance between a point on the boundary to the center of the enclosed boundary of the particle. For a circle, the boundary distance is constant. For a particle with irregular shape, the mean value and standard deviation of the boundary distance reflect the variation (roughness) of the boundary.

Convexity- It is a measure of the smoothness of the particle boundary and defined as the perimeter of the convex hull of particle divided by the actual perimeter of the particle. The convex hull of particle is considered to be the particle surrounded by a ‘rubber band’ as shown in Fig 5 [16]. The greater the convexity, the smoother the particle surface. Let P_c be the perimeter of the convex hull and *P* the actual perimeter of the particle image. Convexity, C_x, is given by,

$$C_x = \frac{P_c}{P}. \tag{5}$$



(a) Particle image with actual boundary.

(b) The convex hull of the particle image (a).

Fig. 5 Particle image with actual boundary and its convex hull.

III. RESULTS AND DISCUSSION

A Image acquisition of a coal particle

A coal sample with size ranging 125-200 μm was dried and injected into the quartz tube of the V-DTF which was preheated at 800°C. The camera tracked and recorded the images of a coal particle during its residence time in the tube at a frame rate of 6200 fps. A total of 528 image frames were captured. Fig. 6 shows the example images of the coal particle. It should be noted that, by the time the camera captured the particle, the coal particle had been in the tube for some time, and thus each image frame does not represent the absolute residence time of the particle in the tube (with reference to time "0" which is the moment when the particle entered the quartz tube), but the relative residence time between frames, e.g., two successive frames represents a relative residence time of 0.2 ms, and 528 frames represent a total relative residence time of 85.1 ms. As can be seen in Fig 6, the size (area) and shape of the particle changed significantly during combustion. As expected, the particle size decreases and the particle shape appears to be irregular, particularly at the later stage of the combustion. The quantification of such variations was performed in terms of the characteristic parameters as defined in section II.

B. Characteristics of the coal particle

Fig. 7 shows the variation of particle area during the residance time in the quartz tube. A decreased trend is shown, but several peaks are also observed around 8 ms (Frame 50), 32 ms (Frame 200), 55 ms (Frame 346), and 82 ms (Frame

510). The periodic variation of the area is believed to be attributed to the rotation of the particle in the line-of-sight direction during combustion.

The circularity ratio is given in Fig. 8. From 1 ms (Frame 1) to 45ms (Frame 280), the circularity ratio ranges mainly between 1 and 1.3, indicating that the shape of the particle is close to a circle. The rapidly increased circularity ratio between 46 ms (Frame 281) and 56 ms (Frame 346) suggests the dramatic variation of the particle shape, which may be attributed to the devolatilization of the particle and volatile combustion around the particle. It is also observed in the video of the particle that some fragments (during the late devolatilization stage and the initial char combustion stage) were broken up from the main particle between 48 ms (Frame 300) and 58 ms (Frame 360). After that, the circularity ratio remains between 1 and 1.3.

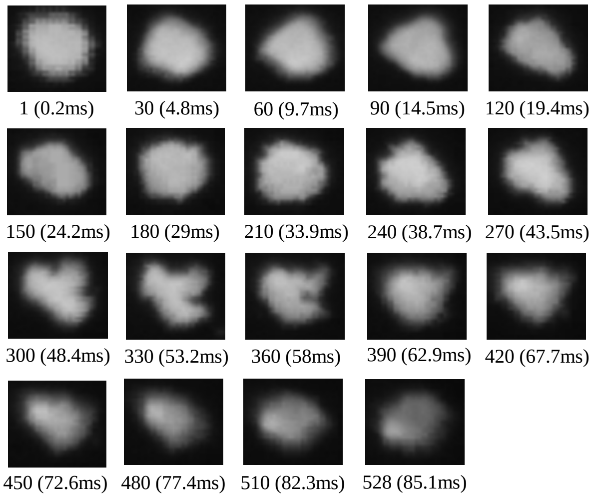


Fig. 6. Example images of the coal particle by frames and relative times.

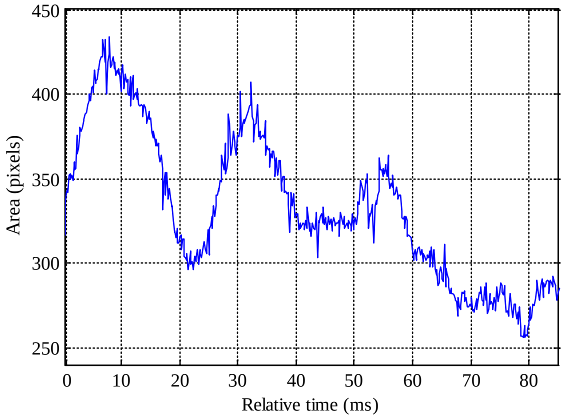


Fig. 7. Area variation of the coal particle in the residence time in the V-DTF.

The variation of the eccentricity is illustrated in Fig. 9. The eccentricity shows a slightly increased trend in general, but a periodic variation is clearly seen. The period is around 27.4 ms (170 frames). A similar periodic variation is also evident in the orientation of the particle, as shown in Fig. 10. Again, the periodic variations in both the eccentricity and orientation are believed to be attributed to the rotation of the particle in the line-of-sight direction during the residence time in the tube.

The boundaries of the particle are also analyzed. Fig. 11 shows the binary images of the particle and the corresponding boundary distance for 56 ms (Frame 346) and 85.1 ms (Frame 528), respectively. As can be seen, the profile of the boundary distances is very different from one frame to another. For a particle image with an irregular shape (as at 56 ms), the boundary distance fluctuates significantly, and vice versa (as at 85.1 ms).

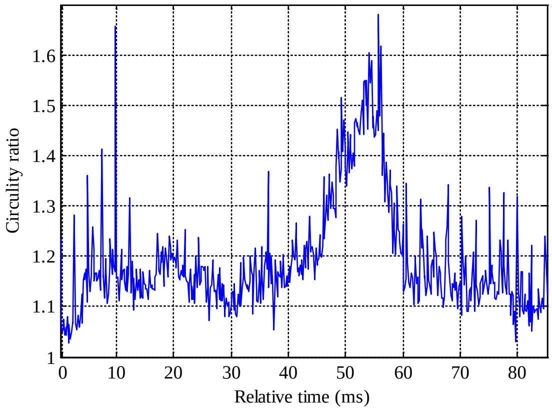


Fig. 8. Circularity ratio of the coal particle.

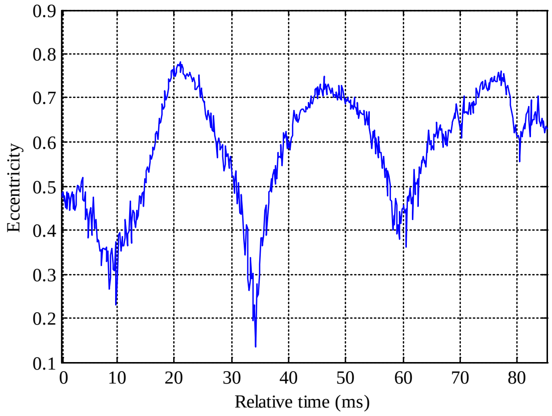


Fig. 9. Eccentricity of the coal particle.

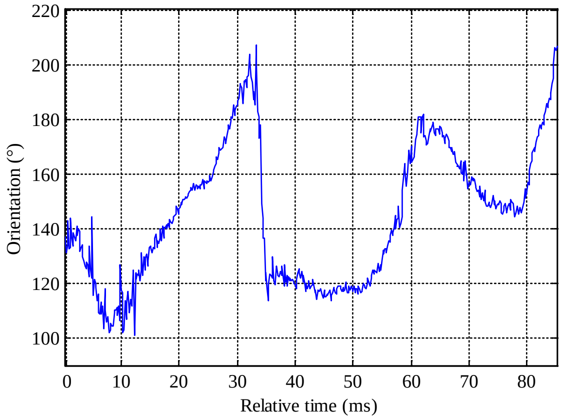
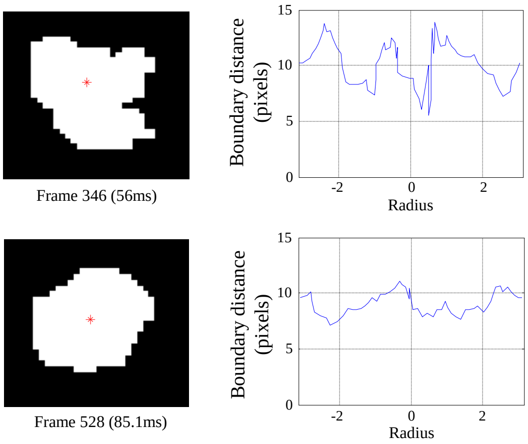


Fig. 10. Orientation of the coal particle.

Figs. 12 to 14 show the variation of the particle boundary parameters. The mean value of the boundary distance (Fig. 12) shows a similar periodic trend as the area (Fig. 8). The maximum standard deviation appears to be at 56 ms (Frame 350, Fig. 13), which is consistent with the direct observation in Fig. 6. The convexity varies generally around ‘1’ between 1ms (Frame 1) and 45 ms (Frame 280) though a few dramatic fluctuations occur in this period of time (Fig. 14). The convexity decreases significantly around 45 ms (Frame 280) and reaches its lowest value at 56 ms (Frame 350). This may be because the coal particle devolatilized at a rate high enough, resulting in volatile combustion at that particular time 45 ms (Frame 280). The convexity appears to increase after 60 ms (Frame 370) and approach to ‘1’, indicating the near completion of the devolatilization/volatile combustion. The results also suggest that the devolatilization/volatile combustion of the particle took about 14.5 ms (90 frames), resulting in around 20% reduction in size and 3% increase in boundary roughness.



Frame 346 (56ms)

Frame 528 (85.1ms)

Fig. 11. Boundary distance of the coal particle for Frames 346 and 528.

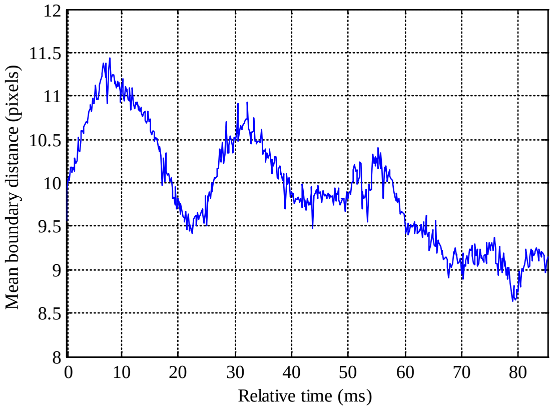


Fig. 12. Mean boundary distance of the coal particle.

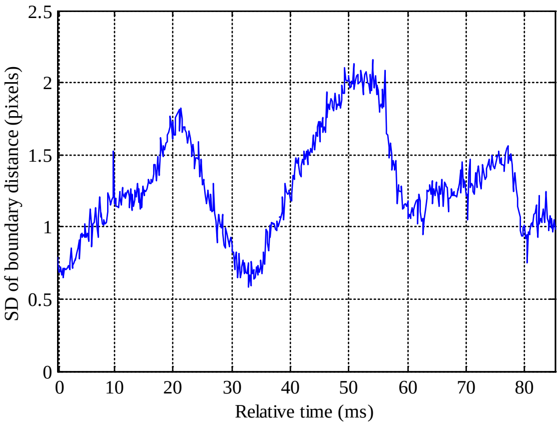


Fig. 13. Standard deviation (SD) of the boundary distance.

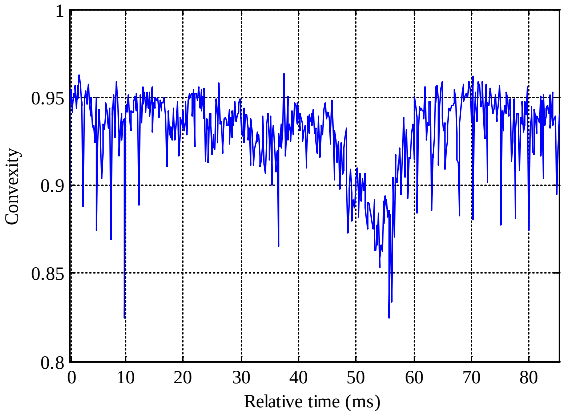


Fig. 14. Convexity of the coal particle.

IV. CONCLUSION

High speed imaging and image processing techniques have been applied for measuring and characterizing the combustion behaviors of single coal particles in a visual drop tube furnace. The images of the coal particle are acquired using a high speed camera and the particle images are processed sequentially. A set of shape and boundary parameters have been defined and computed, which are then used to characterize the coal particle during its residence time in the furnace. The experimental results have demonstrated that the combination of high speed imaging and image processing has provided an effective means for the quantitative measurement and characterization of the combustion behaviors of fuel particles during their residence time in the furnace.

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