SURFACE AREA, VOLUME, MASS, AND DENSITY DISTRIBUTIONS FOR SIZED BIOMASS PARTICLES

FINAL TECHNICAL REPORT

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Surface Area, Volume, Mass, and Density Distributions for Sized Biomass Particles

ABSTRACT

This final technical report describes work performed at Morehouse College under DOE Grant No. DE-FC26-04NT42130 during the period July 01, 2004 to June 30, 2007 which covers the entire performance period of the project. 25 individual biomass particles (hardwood sawdust AI14546 in the size range of 100-200 microns) were levitated in an electrodynamic balance (EDB) and their external surface area, volume, and drag coefficient/mass (C_d/m) ratios were characterized applying highly specialized video based and high-speed diode array imaging systems. Analysis methods were employed using shape and drag information to calculate mass and density distributions for these particles. Results of these measurements and analyses were validated by independent mass measurements using a particle weighing and counting technique. Similar information for 28 PSOC 1451D bituminous coal particles was retrieved from a previously published work. Using these two information, density correlations for coal/biomass blends were developed. These correlations can be used to estimate the density of the blend knowing either the volume fraction or the mass fraction of coal in the blend. The density correlations presented here will be useful in predicting the burning rate of coal/biomass blends in cofiring combustors. Finally, a discussion on technological impacts and economic projections of burning biomass with coal in US power plants is presented.

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INTRODUCTION

The term biomass refers to material of terrestrial plant origin. Hardwoods, softwoods, wheat straw, corn kernel, cassava roots, sugar cane bagasse, and coconut shells are some of the largely available agricultural biomass materials. Wood is one of the most important biomass materials that could potentially be diverted to other uses. The amount of biomass produced has been estimated to be 170 billion tons per year, of which about 70% is from forests [1]. An estimate of the amount of biomass available in the U.S. for conversion to fuels or chemicals is 2 billion tons per year [2]. The conversion of 20% of this material provides an energy equivalent of 6.5 x 1015 BTU, roughly 10% of the U.S. annual energy needs [1].

The political (indigenous supply) and environmental (low sulfur, no net CO_2, biodegradable) benefits of using biomass will continue to provide impetus to the development of cofiring coal with biomass feed stocks. Cofiring of biomass and coal has been identified as a promising way of reducing net CO_2 emissions with minimum modifications in the existing technologies. In fact, some developed countries, e.g., Denmark, have already mandated the use of coal biomass blends in all coal fired boilers. Coal and biomass are certain to remain a primary source of energy for at least several decades, and this is why a great need exists to develop modern combustion systems characterized by high carbon utilization (combustion efficiency) and low emission of pollutants (SO_2, NO_x, N_2O, air toxics, etc.). One of the most important factors affecting the performance of utility boilers is fuel type. In some cases, blending biomass with coal may solve a pollution compliance problem or an operational problem or provide an economic benefit.

Coal and biomass particles are irregular in shape. Early attempts to characterize shape relied primarily on sieve analyses to classify particle "size." This approach was subsequently augmented by microscopic measurements and sizing methods based on sedimentation rates in fluids. These methods however, give no indication of the inclination of the axes of the body with respect to three coordinates, the type of geometrical shape, the volume or the surface area [3]. Heywood [4] dealt with this issue by defining shape-dependent coefficients in his analysis of volume and surface area. These coefficients are functions of the proportions of the particle, i.e., the relative values of breadth (B), thickness (T), and length (L). These are obtained by resting the particle in its most stable position. Breadth, B, is defined as the minimal distance between two parallel tangents to the profile or outline of the particle, length, L, is defined similarly but taken at right angles to the breadth, and thickness T, is the height normal to the resting plane.

Detailed information on shape, drag, volume, density, and surface area is needed to improve our understanding of transport phenomena of irregular particles. From a fluid mechanics standpoint, a data base on various shapes of particulates would enhance the current ability to design and analyze feeder systems, cyclones, fluidized beds, and particulate separation systems. From a heat and mass transfer perspective, particle mass and shape are important considerations. In general, to simplify the analysis, heat transfer calculations are performed assuming particles to be spheres. Several studies have been published in recent years where this approach has been used and temperature measurements have been compared with model predictions [5-7]. In each of these studies, however, large empirical corrections were required in order to match model predictions with measurements. Maloney and coworkers [5] concluded that these corrections were necessary primarily because of the shape and density, and thermal property assumptions applied in the heat transfer analysis.

Energy absorption and emission mechanisms depend on a particle's surface area whereas its temperature response depends strongly on mass (ρv). For irregular particles such as coal, the equivalent diameters for external surface area and volume can differ significantly [8]. Moreover, the density for these particles is found to be non-uniform [8]. Hence, in-situ measurement of particle shape and density in addition to temperature measurement would allow one to better characterize and predict the thermal transport characteristics of coal particles during devolatilization and combustion. Hurt and Mitchell [9] reported large particle-to-particle temperature variations in their combustion studies of single char particles. They concluded that particle-to-particle variations in physical properties are a leading cause of these large temperature differences. Thus, individual particles have unique surface area, volume, and density and a unified approach comprising measurements of these properties is necessary if reliable predictions of transport phenomena are to be achieved.

In pursuit of this unified approach, various experimental techniques were developed recently in the single particle laboratory at the National Energy Technology Laboratory (NETL), Morgantown. These techniques involve the use of an electrodynamic balance (EDB) to characterize particle properties. The principal advantage of this instrument is the capability of suspending a charged particle motionless at the balance's geometric center, thus facilitating particle characterization.

Using a video-based imaging system, Maloney et al. [10] developed capabilities for measuring 3-D surface areas and volumes of irregular particles. Individual particles were rotated about the EDB center axis using a set of tangentially directed gas jets. As the particle rotates, a video-based imaging system records the particle images and stores perimeter data from successive video fields. Rotation rates were measured with the aid of a second video system positioned above the balance. Surface areas and volumes were calculated by summing the surface and volume elements swept out during rotation from one video field to the next.

Maloney et al. [11] also developed capabilities for measuring drag coefficient/mass ratios (C_d/m) for particles in the EDB. Using a high-speed diode array imaging system, they measured particle trajectories resulting from an applied stimulus. Particle C_d/m ratios were found from these trajectory measurements by means of a force balance model which matched theoretical predictions with measurements. Surface area and volume data were then used to estimate the particle drag coefficient by applying an analysis for deformed spheres derived by Brenner [12]. The particle mass was then calculated based on the measured C_d/m and the calculated drag coefficient [8].

Sampath [13] developed a second method of characterizing the volume, external surface area, and drag equivalent diameter of an irregular particle based on conventions established by Heywood [4]. This method incorporated the same EDB measurement system and associated instruments that were developed by Maloney et al. [10] to characterize irregular particles. In this method, irregular particles were characterized by obtaining directly the magnitudes of length, breadth, thickness, and projected areas from two view images in the planes parallel and perpendicular to the orientation of the particle during the measurement. The C_d/m ratio was also found for individual particles. This ratio was then used to obtain particle mass and density. A mean particle mass for the sample studied was obtained using a direct gravimetric method [8,13]. This method involved weighing and counting several thousand coal particles. Finally, the mean mass obtained using the EDB measurement system was validated by comparison with the results of the direct gravimetric method.

In view of the anticipated rapid development of technologies for co-feeding of coal and biomass, a great need exists for the development of a data base on the shape and density distributions of biomass particles for use in combustion models. Detailed property data including surface area, volume, mass, and density distributions for several coal samples are now available [8,13] for use in coal combustion models.

To this end, applying our experimental and analytical capabilities in the particle characterization research [5,8,10-11,13], this project sought to characterize the shape and mass for biomass particles. Following the approach of Maloney et al. [10], individual biomass particles were characterized for their external 3-D surface area and volume, and drag coefficient/mass ratios. Analysis methods were employed using shape and drag information to calculate mass and density distributions for these particles. Results of these measurements and analyses were validated by independent mass measurements using a particle weighing and counting technique.

The specific objectives were:

1) Apply unique measurement systems to characterize external surface area, volume, mass, and density for a statistically significant number of individual biomass particles (20 particles) in the size range of 100 - 200 μm.

2) Obtain mean mass per particle of the biomass sample tested in Objective (1) by independent mass measurements of several thousand particles using a particle weighing and counting technique.

Experiments and data analysis were carried out to meet the project objectives. Mean mass of several thousand biomass particles obtained in Objective (2) were used to validate the mean mass per particle obtained in Objective (1). Cofiring of biomass and coal has been identified as a promising way of reducing net CO_2 emissions with minimum modifications in the existing technologies. The successful accomplishment of the above objectives provides detailed particle property data required for developing improved combustion kinetic models for technologies involving cofiring of coal and biomass feedstocks.

EXECUTIVE SUMMARY

In this final technical report, the work performed under DOE Grant No. DE-FC26-04NT42130 during the period July 01, 2004 to June 30, 2007 is described and the accomplishments are highlighted summarizing the most important research results.

Over the next decade there will be a renewed emphasis on cofiring biomass with coal. Cofiring of biomass and coal has been identified as a promising way of reducing net CO_2 emissions with minimum modifications in the existing technologies. Coal and biomass particles are irregular in shape. From a combustion perspective, particle sphere assumptions employed in most coal combustion models were found to yield significant errors (20 to 25 percent) in calculated particle volume and associated thermal mass. Even if surface area and volume differences were adequately handled in a heat transfer analysis, large uncertainties still resulted in coal particle temperature response due to particle to particle density variations. Recently, shape and density for coal particles have been characterized [14] and detailed property data including surface area, volume, mass, and density distributions for several coal samples are now available for use in coal combustion models.

This project sought to characterize the shape and mass for biomass particles. Individual biomass particles were levitated in an electrodynamic balance (EDB) and their external surface area, volume, and drag coefficient/mass (C_d/m) ratios were characterized applying highly specialized video based and high-speed diode array imaging systems. Analysis methods were employed using shape and drag information to calculate mass and density distributions for these particles. Results of these measurements and analyses were validated by independent mass measurements using a particle weighing and counting technique. Experiments involving counting and weighing of several thousand biomass particles employing a microscope and a sub-milligram balance experimental system were performed by Morehouse College in Atlanta. Experiments involving imaging systems were performed by REM Engineering Services, our subcontractor in this project, using the EDB measurement system available at the single particle laboratory, National Energy Technology Laboratory (NETL), Morgantown. Morehouse analyzed the raw data collected in this project including that by REM. The successful accomplishment of the above goals provides detailed particle property data required for developing improved combustion kinetic models for technologies involving cofiring of coal and biomass feedstocks.

Characterization of surface area, volume, mass, and density distributions for 25 biomass particles has been completed in this project. Similar information for 28 PSOC 1451D bituminous coal particles was retrieved from a previously published work. Using these two information, density correlations for coal/biomass blends were developed based on two approaches: 1) volume fraction, and 2) mass fraction of coal in the blends, and are presented here. These correlations will be useful in predicting the burning rate of coal/biomass blends in cofiring combustors. Finally, a discussion on technological impacts and economic projections of burning biomass with coal in US power plants is provided.

EXPERIMENTAL

In this project, characterization of surface area, volume, mass, and density distributions for 25 biomass particles has been carried out employing the unique EDB measurement system available at NETL, Morgantown. Also, counting and weighing measurements were carried out to obtain the mean mass for several thousand biomass particles tested in this study. The biomass particles (hardwood sawdust AI14546) in the size range of 100-200 microns were obtained from a cofiring pilot plant research facility owned by Southern Company, Birmingham, AL. The experimental techniques involving the EDB system and the gravimetric approach in obtaining the raw data discussed above are presented below.

Measurement of Particle C_d/m, External Surface Area, Volume, Mass, and Density:

Individual biomass particles were levitated in the electrodynamic balance (EDB) and characterized using high-speed optical and electronic instruments. Single particles were backlit with a red He:Ne laser at the side and with a light emitting diode (LED) from the bottom of the balance. The magnified shadow image of the side view was split and projected onto the detector of a CCD video camera imaging system and a high-speed diode array imaging system. The magnified shadow image of the bottom view was projected onto the detector of a second CCD video camera imaging system positioned above the balance. The video-based imaging systems (side and top) were used for shape characterization. The diode array imaging system was used to characterize particle drag coefficient/mass (C_d/m) ratios.

The calibration procedure of the video-based imaging system involved suspending DVB (divinyl benzene) spheres in the electrodynamic balance (EDB). The spheres were backlit with a He:Ne laser at the side and a LED from the bottom. The side view is projected onto the detector of a video camera and a photodiode array. The bottom view is projected onto the detector of a second video camera positioned above the balance. The horizontal counts and the vertical lines blocked by the projected images are recorded in both cameras. The total number of horizontal counts blocked is proportional to the cross-sectional area of the sphere. Similarly, the total number of pixels blocked is proportional to the cross-sectional area of the sphere. The sphere was then retrieved from the EDB and sized to within ∀ 2 m diameter using an optical microscope. This procedure was repeated for a number of calibration spheres in the particle size range of interest (64 - 230 μm).

The diode-array imaging system is used to measure the trajectory of the particle in the electrodynamic balance (EDB) resulting from an applied stimulus. The array is made of 16 x 62 elements of silicon photodiodes spaced 100 μm apart. A magnified image of the particle projected onto the array blocks a certain number of photodiode elements yielding an output in volts that is proportional to the location of the particle in the EDB.

The position calibration involved the following procedure. A polystyrene sphere was placed on a glass plate. The glass plate was suspended in the center of the balance by a clamp. The clamp was attached to an extended pole system mounted on a XYZ translation stage. The flat portion of the plate was aligned perpendicular to a He:Ne laser beam. Next the XYZ stage was translated until a good focus of the polystyrene sphere was observed at the bottom of the monitor. The micrometer reading of the XYZ stage (in mm) and the diode-array output (in volts) are recorded. The particle was moved 50 micron increments until it was seen at the top of the monitor. Each time the particle was moved, the micrometer reading and the diode-array output were recorded.

Following the calibration of the imaging systems, particle C_d/m ratios were determined based on measurements of particle trajectory in the EDB. Individual biomass particles were balanced in the EDB and a step change was applied to the EDB endcap voltage, stimulating a dynamic response of the particle from its balance position. The resulting transient motion of the particle was measured using the high-speed diode array imaging system which provided an analog output indicating particle position along the EDB center axis. A force balance model referred to as the Particle Dynamic Model (PDM) was used to simulate the particle trajectory in the EDB. The only unknown in the force balance was particle C_d/m which was determined by matching the model output with the measurements. The details of the C_d/m measurement can be obtained elsewhere [11].

Following the approach of Maloney et al. [10], raw data for volumes and external surface areas for 25 individual biomass particles were obtained by rotating particles and recording image data for successive video fields as a function of rotation angle using side view video imaging system. Particles were rotated about the EDB center axis using six directed gas jets equally spaced about the EDB centerplane. Rotation rates were established in the range of 10 to 15 revolutions per minute and were determined with the aid of the top view video camera.

In a previously published work [14], measurements were made on individual particles of PSOC 1451D bituminous coal in the aerodynamic size range of 106 - 125 μm to study the effect of heating rate on the thermal properties of pulverized coals. Various heat fluxes ranging from 700 to 1600 W/cm^2 were employed to heat the particles. The coal was collected by the Coal Research Section of the Pennsylvania State University and aerodynamically size classified by Vortec Products Co. The D designation indicates that the sample was part of a DOE effort to generate and distribute a common suite of coal samples to a number of independent research laboratories.

Mean Mass Measurements by Gravimetric Technique:

Mean particle mass for the biomass sample tested was obtained using a direct gravimetric measurement system that was set up at Morehouse College in this project. This involved weighing and counting several thousand biomass particles. A paper boat was made with a grid paper and its empty weight measured using a sub- milligram balance (uncertainty ± 10 μg). Several thousand biomass particles were dispersed on the grid surface and the weight of the particles plus the boat was measured. The particles were then counted under a microscope. The experiment was repeated several times to obtain a statistically significant mean mass value of the sample studied.

Dry and As Received analysis of the biomass particles tested in the present study is provided in Table 1 below. Ultimate and proximate analyses of the coal sample studied earlier are presented in Table 2.

TABLE 1
Dry and As Received Analysis for A114546 Hardwood Sawdust Biomass:
(As reported by Southern Company Services, Birmingham, AL)

ANALYSIS % BY WEIGHT	DRY BASIS
% Ash % S	0.61 0.02
ANALYSIS % BY WEIGHT	AS RECEIVED BASIS
% Moisture % Ash % S	11.32 0.54 0.02

TABLE 2
Ultimate and Proximate Analysis for PSOC 1451D Bituminous Coal:
(As reported by the Penn State Office of Coal Research)

ULTIMATE ANALYSIS	DRY ASH FREE BASIS
% Carbon % Hydrogen % Nitrogen % S + O (diff)	83.3 5.4 1.6 9.7
PROXIMATE ANALYSIS	AS RECEIVED BASIS
% Moisture % Ash % Volatile Matter % Fixed Carbon	2.5 13.3 33.6 50.6

RESULTS AND DISCUSSION

Results of Shape and Mass Measurements for Biomass Particles:

The calibration plots for the Side and Top View Imaging Systems are provided in Figures 1 and 2. The calibration equations are presented in each of the plots. The R squared value in these equations is greater than 0.99. This yielded a single size measurement with an uncertainty of not more than ∀ 5 μm (worst case) over the entire particle size range (64 to 230 μm) tested.

The calibration plot for particle position versus diode-array output for particle travel from bottom-to-top is provided in Figure 3. The calibration equation is presented in the plot. The R squared value in this equation is greater than 0.99. The slope of this line yielded the distance moved by the particle per volt and was found to be 362 ∀ 01 μm/volt.

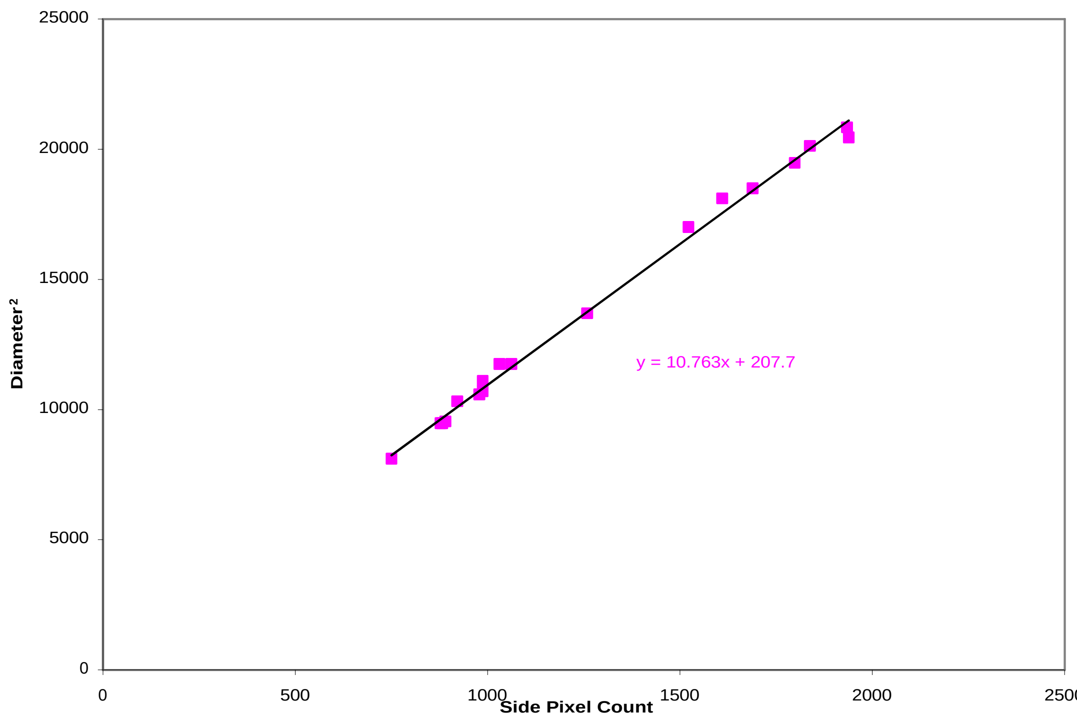

Figure 1. Side Imaging System Calibration

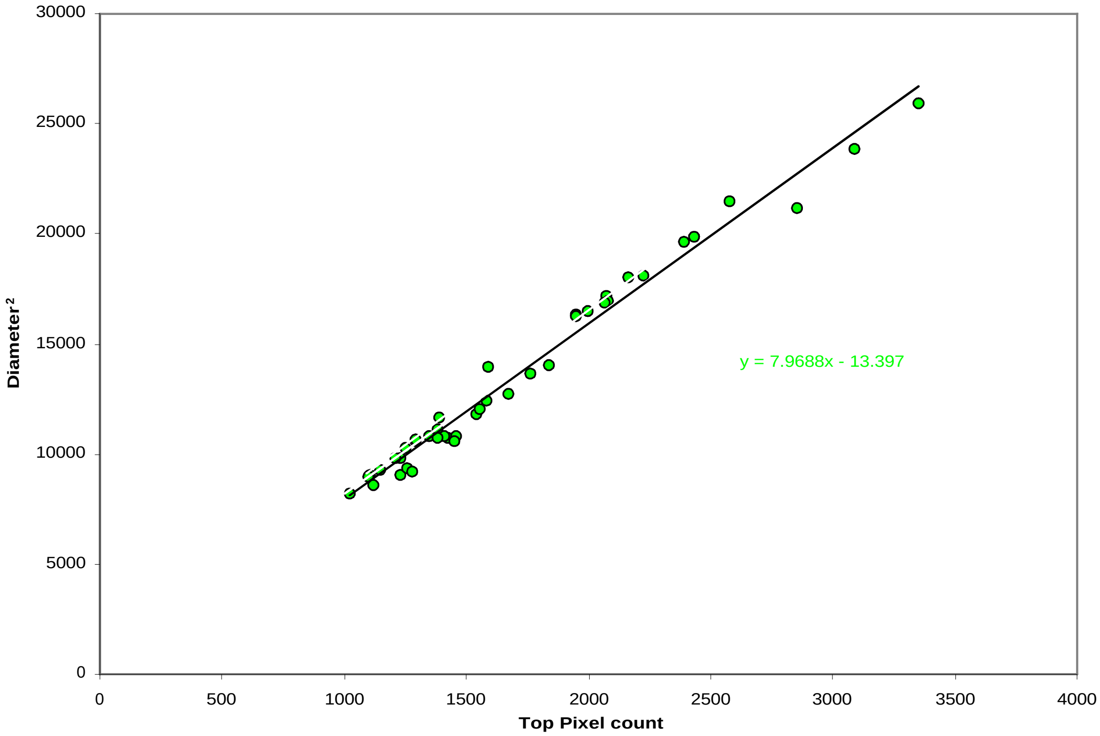

Figure 2. Top Imaging System Calibration

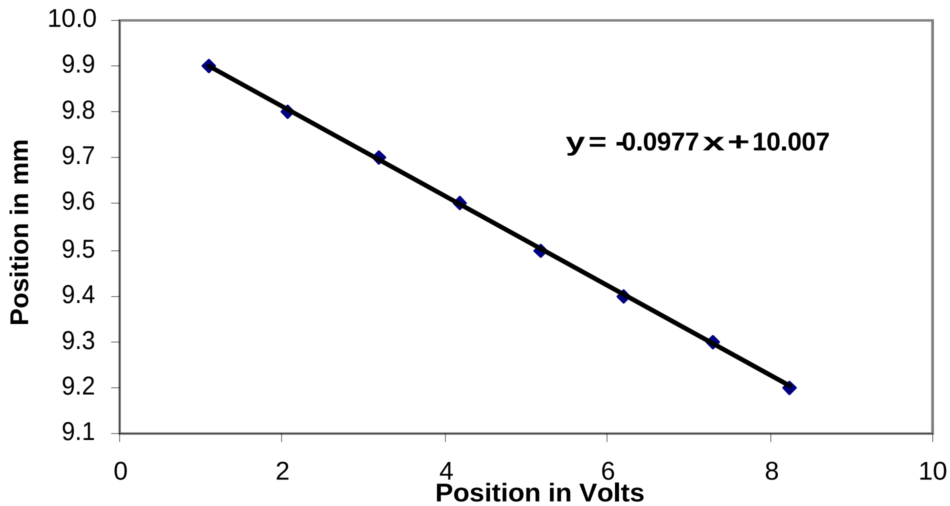

Figure 3. Position Voltage Calibration

REM collected raw data for a total of 25 biomass particles employing the EDB measurement system discussed before. Briefly, individual particles were rotated about the EDB center axis using a set of tangentially directed gas jets. As the particle rotates, a video-based imaging system records the particle images and stores perimeter data from successive video fields. Rotation rates were measured with the aid of a second video system positioned above the balance. Morehouse analyzed the raw data and calculated 3-D surface areas and volumes following the procedures explained by Monazam et al. [8]. Surface areas and volumes were calculated by summing the surface and volume elements swept out during rotation from one video field to the next. From the surface area and volume, surface area equivalent diameter (d_{sa}), and volume equivalent diameter (d_v) were obtained. The observed surface area and volume was used to estimate particle drag coefficient by applying Brenner's approach [12] for deformed spheres. The particle mass was then separated from the C_d/m ratio. From the mass and volume, the particle density was determined. Complete details of the video imaging system and the experimental determination of particle 3-D surface area, volume, mass, and density can be obtained elsewhere [8]. Results of the shape information (equivalent diameters for particle surface area (d_{sa}), volume (d_v)), and particle C_d/m, mass (m), and density (ρ) information obtained for 25 individual biomass particles examined in this study are presented in Table 3. Similar information for 28 PSOC 1451D coal particles retrieved from one of our earlier work is presented in Table 4. Using these two information, density correlations for coal/biomass blends were developed in this project. These correlations can be used to estimate the density of the blend (ρ_{bl}) knowing either the volume fraction (V_{fc}) or the mass fraction (M_{fc}) of coal in the blend.

Derivation of the density correlation for the blend as a function of the mass fraction of coal (M_{fc}) is provided below. Abbreviation of the symbols is presented in the nomenclature.

$$\ell_{bl} = \frac{M_{bl}}{V_{bl}} \quad \ldots\ldots\ldots\ldots(1)$$

where

$$M_{bl} = M_c + M_b \quad \ldots\ldots\ldots\ldots(2)$$

and

$$V_{bl} = V_c + V_b \quad \ldots\ldots\ldots\ldots(3)$$

$$M_{fc} + M_{fb} = 1 \quad \ldots\ldots\ldots\ldots(4)$$

$$M_c = M_{fc} M_{bl} \quad \ldots\ldots\ldots\ldots(5)$$

$$M_b = (1 - M_{fc}) M_{bl} \quad \ldots\ldots\ldots\ldots(6)$$

$$V_c = \frac{M_{fc} M_{bl}}{\rho_c} \quad \ldots\ldots\ldots\ldots(7)$$

$$V_b = \frac{(1 - M_{fc}) M_{bl}}{\rho_b} \quad \ldots\ldots\ldots\ldots(8)$$

$$V_{bl} = \frac{(M_{fc}\rho_b + \rho_c - M_{fc}\rho_c) M_{bl}}{\rho_b \rho_c} \quad \ldots(9)$$

$$\rho_{bl} = \frac{\rho_b \rho_c}{(M_{fc}\rho_b + \rho_c - M_{fc}\rho_c)} \quad .....(10)$$

Substituting ρ_c and ρ_b with the average densities for biomass and coal (0.8 and 1.13 g/cm^3) from Tables 3 and 4, the density of the blend as a function of the mass fraction of coal in the blend can be obtained using the following correlation:

$$\rho_{bl} = \frac{0.904}{(1.13 - 0.33M_{fc})} \quad ....(11)$$

Derivation of the density correlation for the blend as a function of the volume fraction of coal (V_{fc}) is provided below.

$$V_{fc} + V_{fb} = 1 \quad ....(12)$$

$$V_c = V_{fc}V_{bl} \quad ....(13)$$

$$V_b = (1 - V_{fc})V_{bl} \quad ....(14)$$

$$M_{bl} = (V_{fc}V_{bl}\rho_c)(1 - V_{fc})V_{bl}\rho_b \quad .....(15)$$

$$\rho_{bl} = (V_{fc}\rho_c)(1 - V_{fc})\rho_b \quad ....(16)$$

Substituting ρ_c and ρ_b with the average densities for biomass and coal (0.8 and 1.13 g/cm^3) from Tables 3 and 4, the density of the blend as a function of the volume fraction of coal in the blend can be obtained using the following correlation:

$$\rho_{bl} = 0.8 + 0.33V_{fc} \quad ....(17)$$

It should be noted that equation 11 reduces to the value of ρ_b when M_{fc} is equal to zero and that of ρ_c when M_{fc} is equal to one. Similarly, equation 17 reduces to the value of ρ_b when V_{fc} is equal to zero and that of ρ_c when V_{fc} is equal to one. Equations 11 and 17 can also be applied to known fractions of mass or volume flow rates of coal in continuous flow processes involving the combustion of coal/biomass mixtures. It also should be noted that equations 11 and 17 are valid only for the blends of bituminous coal and saw dust particles found in the US.

Result of the direct gravimetric method:

A total of 32,133 particles were weighed and counted in a number of batches and the mean mass per particle was found to be 1.823 x 10^{-7} g.

Validation of single particle mass measurement:

The mean mass of 25 individual biomass particles obtained employing the EDB system is found to be 1.83 x 10^{-7} g and is presented in Table 1. It should be noted that this mean mass is to within ±1% of that obtained by the gravimetric approach discussed above.

TABLE 3
Shape, Mass, and Density Information for Biomass Particles

Particle #	Surface Area Diameter, d_{sa} (μm)	Volume dia, d_v (μm)	C_d/m (1/s)	mass, m (μg)	density, ρ (g/cm^3)
1	119.10	112.45	63.7	0.270	1.19
2	72.30	65.28	119.2	0.092	1.19
3	80.04	75.02	77.6	0.172	1.21
4	78.56	73.85	64.7	0.204	1.02
5	121.53	106.92	108.1	0.173	0.74
6	98.05	89.66	110.0	0.134	0.77
7	98.95	91.39	80.2	0.191	0.68
8	117.73	110.43	50.1	0.387	0.76
9	115.80	100.77	89.0	0.201	0.81
10	99.00	89.85	43.0	0.344	1.11
11	125.85	117.20	34.4	0.579	0.71
12	66.79	61.35	191.3	0.055	0.53
13	99.72	90.62	60.8	0.269	0.78
14	97.64	90.88	150.3	0.097	0.75
15	88.48	78.88	216.5	0.063	0.97
16	99.30	86.01	106.2	0.151	0.78
17	97.79	88.25	84.5	0.198	0.65
18	105.35	98.42	95.3	0.174	0.74
19	97.22	87.49	69.4	0.228	0.87
20	87.30	78.09	133.3	0.103	0.65
21	73.37	71.35	137.4	0.085	0.70
22	90.40	79.92	129	0.106	0.68
23	111.20	100.40	164.3	0.107	0.37
24	94.57	82.25	127.2	0.123	0.50
25	82.41	78.91	190.1	0.063	0.92
Average	96.74	88.23	107.82	0.183	0.80

TABLE 4
Shape, Mass, and Density Information for PSOC 1451D Bituminous Coal Particles

Particle #	Surface Area Diameter, d_{sa} (μm)	Volume dia, d_v (μm)	C_d/m (1/s)	mass, m (μg)	density, ρ (g/cm^3)	Time-Averaged Intensity, I(ta) (W/cm^2)
1	93	85	49	0.37	1.12	N/A
2	104	97	33.5	0.58	1.20	717
3	105	99	36	0.54	1.06	727
4	129	117	30	0.86	1.04	745
5	113	108	29	0.71	1.08	763
6	102	96	28	0.68	1.45	764
7	141	123	27	1.15	1.18	894
8	103	96	34	0.58	1.24	906
9	87	83	40	0.39	1.29	1092
10	126	116	25	0.98	1.19	1105
11	125	118	26	0.9	1.05	1138
12	117	111	26	0.82	1.14	1209
13	124	118	24	0.94	1.09	1302
14	134	125	23	1.1	1.09	1319
15	108	102	30	0.66	1.18	1328
16	109	106	28	0.7	1.13	1402
17	99	92	35	0.54	1.33	1453
18	105	101	31	0.61	1.14	1469
19	104	100	32	0.59	1.14	1475
20	115	110	28	0.74	1.08	1482
21	112	106	27.5	0.75	1.21	1488
22	101	94	33	0.57	1.30	1494
23	123	115	22.5	1.03	1.28	1500
24	108	101	32	0.63	1.15	1506
25	107	100	28	0.71	1.36	1507
26	103	95	52	0.38	0.84	1507
27	126	115	27	0.91	1.14	1511
28	155	143	80	0.38	0.25	1542
Average	114	106	33	0.71	1.13	1235

Technological Impacts and Economic Projections of burning Biomass with Coal:

It is accepted that CO_2 emissions from burning fossil fuels such as coal and petroleum contribute to global warming and climate change. However, CO_2 produced from burning biomass is considered carbon-neutral because the carbon in biomass is part of the active carbon cycle. In addition to reduced emissions of $CO_{2,}$ potential benefits of cofiring biomass with coal include reduced emissions of sulfur and nitrogen oxides.

Technological Impacts:

In the last ten years, numerous demonstrations have been performed using commercial coal combustors in the U.S. to evaluate the technological impacts of burning biomass with coal [15-29]. These demonstrations indicate that there are no major technical obstacles to implementing cofiring.

Coal combustors are designed to operate on a fuel with a given set of properties. Jenkins et al. [29] critically assessed the impact of cofiring comparing the differences in fuel properties between biomass and coal. Biomass differs from coal in both physical and thermodynamic properties including inorganic composition, fibrous nature, moisture content, energy density, volatile content, heat capacity, and thermal conductivity. Jenkins et al. [29] concluded that fuel properties outside of the design range can adversely impact the performance of the combustors.

Existing coal processing and delivery systems are designed to handle pulverized coal fuels. Biomass is premixed with the coal and delivered to the combustor using the existing coal feeding system [15,27,30]. Biomass has low density and high moisture content. This creates fuel-feeding challenges in cofiring biomass with coal. The exact level of cofiring that can be achieved depends on the level of biomass cofeeding capacity at a particular power plant. This is found to be in the range of 2-20% percent biomass by energy at full load. Once this limit is reached, higher levels of cofiring was found to reduce the capacity of the power plant [20]. To achieve higher levels of cofiring without reducing the capacity of the power plant, a separate biomass preparation and feeding system is found to be required. Swanekamp [25] reported cofiring levels as high as 40% biomass by energy with no loss in capacity using separate feeding systems.

The reduction in boiler efficiency in cofiring is found to be largely due to the higher moisture content of the biomass fuel compared to the coal. Tillman et al. [17-18] reported higher efficiencies when cofiring a dry biomass with a wet coal.

The size of biomass particles involved in cofiring is found to be larger than that of pulverized coals. This is a concern in cofiring that produces unburned carbon, hence particulate pollution and reduction in efficiency. Boylan [26] demonstrated smaller amount of particulate emission with proper preparation of the biomass feed.

Ash deposition is common in the operation of power plants that operate on coal, biomass, and other ash-forming fuels. Commercial scale cofiring demonstrations indicate that cofiring coal with clean wood wastes does not create ash deposition problems as these wastes have low ash and alkali levels [15].

Cofiring reduces SO_x emissions because biomass fuels contain little or no sulfur [29]. It also reduces NO_x, because biomass fuels contain low nitrogen levels.

Torrefaction is a thermal process to improve the energy content of biomass, which involves the heating of biomass to moderate temperatures (200-300 °C). At these temperatures, chemically bound water can be released from the biomass, increasing the carbon content and the heat of combustion. During torrefaction biomass undergoes changes in physical and chemical properties. There is also the benefit that the biomass becomes more hydrophobic after torrefaction. This can be particularly important for energy densification or pellet making. Finally, there is the possibility that torrefaction could be used to increase the density of biomass pellets close to that of pulverized coals. Improvement of grindability and fluidization properties of biomass through torrefaction is seen as a promising pretreatment option to implement large-scale cofiring of coal/biomass blends [31].

Economic Projections:

Amount of energy produced in the U.S. burning biomass is currently estimated to be about 3%, however, biomass is predicted to contribute to a significantly larger percentage of the energy needs in the future [32-33].

Numerous commercial-scale demonstrations indicate that cofiring biomass with coal is economically feasible [15-26]. Existing coal combustors can be retrofitted to burn coal biomass blends incurring only small expenses over a time frame of 1-2 years. The lower heating value and higher moisture content can be problematic, however, no significant reduction in plant efficiency has been reported when the fraction of biomass mixed is in the range of 2-20% [15,18-20,26]. Regular supply of biomass fuel around the year can be a problem and this can be tuned to the seasonal availability of biomass adjusting the coal-biomass blend within the above range. The higher heating value efficiency penalty associated with the moisture in biomass can be avoided by drying the fuel before cofiring. The high cost of biomass, however, remains a problem [16,30,34-35].

Robinson et al. [36] analyzed the economics of cofiring biomass in existing coal-fired power plants using currently available agriculture and forest product residues. They developed a model to calculate electricity and pollutant mitigation costs with explicit characterization of uncertainty in fuel and retrofitting costs and variability in fuel properties. The model was first used to evaluate the plant-level economics of cofiring as a function of biomass cost. It was then integrated with state-specific coal consumption and biomass supply estimates to develop national supply curves for electricity and carbon mitigation. A delivered cost of biomass below $15 per ton was found to be required for cofiring to be competitive in existing coal combustors.

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Outcome to-date

Several experiments and theoretical analyses were conducted in this project. These activities resulted in several reports, and conference presentations and are listed below.

1. Sampath, R., Dixon, R. M., Young, M. D., Weirko-Brobby, G., Surface Area, Volume, Mass, and Density Distributions for Sized Biomass Particles, 2005 University Coal Research / Historically Black Colleges and Universities and other Minority Institutions Contractors Review Meeting, sponsored by NETL/U.S. DOE, June 7-8, 2005, Pittsburgh, PA.

2. Sampath, R., Brown, C. S., and Monazam, E. R., Surface Area, Volume, Mass, and Density Distributions for Sized Biomass Particles, First Semi-Annual Progress Report submitted to NETL/DOE, Pittsburgh, January 2005.

3. Sampath, R., Brown, C. S., and Monazam, E. R., Surface Area, Volume, Mass, and Density Distributions for Sized Biomass Particles, Second Semi-Annual Progress Report submitted to NETL/DOE, Pittsburgh, July 2005.

4. Sampath, R., Brown, C. S., and Monazam, E. R., Surface Area, Volume, Mass, and Density Distributions for Sized Biomass Particles, Third Semi-Annual Progress Report submitted to NETL/DOE, Pittsburgh, January 2006.

5. Brown, C. S., Sampath, R., Byars, M., Saha, G., and Monazam, E. R., Surface Area, Volume, Mass, and Density Distributions for Sized Biomass Particles, 2006 University Coal Research / Historically Black Colleges and Universities and other Minority Institutions Contractors Review Meeting, sponsored by NETL/U.S. DOE, June 6-7, 2006, Pittsburgh, PA.

6. Sampath, R., Brown, C. S., Monazam, E. R., and Byars, M., Surface Area, Volume, Mass, and Density Distributions for Sized Biomass Particles, 2007 University Coal Research / Historically Black Colleges and Universities and other Minority Institutions Contractors Review Meeting, sponsored by NETL/U.S. DOE, June 5-6, 2007, Pittsburgh, PA.

CONCLUSION

Cofiring of biomass with coal has been identified as a promising way of reducing net CO_2, NO_x, and SO_x emissions with minimum modifications in the existing technologies. Also, close to 100% plant efficiency has been reported from pilot plants burning biomass with coal, when the fraction of biomass mixed is in the range of 2-20%. While cofiring biomass is good for the environment, still more research needs to be carried out to understand the burning rate of coal biomass blends. Coal and biomass particles are irregular in shape. Accurate shape and density information is necessary for reliable prediction of burning behavior of coal/biomass blends in combustors. Recently, shape and density for coal particles have been characterized and detailed property data including surface area, volume, mass, and density distributions for several coal samples are now available for use in coal combustion models. In the present study, 25 individual biomass particles (hardwood sawdust AI14546 in the size range of 100-200 microns) were levitated in an electrodynamic balance (EDB) and their external surface area, volume, and drag coefficient/mass (C_d/m) ratios were characterized applying highly specialized video based and high-speed diode array imaging systems. Analysis methods were employed using shape and drag information to calculate mass and density for these particles. The mean mass of 25 individual biomass particles thus obtained was found to be 1.83 x 10^{-7} g. This mean mass value was verified in a separate experiment, using a gravimetric approach. Under this approach, a total of 32,133 biomass particles were weighed and counted in a number of batches. The mean mass per particle in this approach was found to be 1.823 x 10^{-7} g and is to within ±1% of that obtained by the EDB method. Similar information of surface area, volume, mass, and density data for 28 PSOC 1451D bituminous coal particles was retrieved from a previously published work. Using these two information, density correlations for coal/biomass blends were developed in this study based on two approaches: 1) volume fraction, and 2) mass fraction of coal in the blends. Coal and biomass particle property data and the density correlations for coal/biomass blends reported in this study will be useful in developing improved combustion kinetic models for technologies involving cofiring of coal and biomass feedstocks.

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NOMENCLATURE

C_d/m	particle drag coefficient/mass ratio (sec^{-1})
d	particle diameter (µm)
M	particle mass in equations 1 to 17
m	particle mass (µg)
V	particle volume in equations 1 to 17
ρ	particle density (g/cm^3)

Subscripts:

b	biomass
bl	blend
c	coal
fc	fraction of coal
sa	of surface area equivalent
ta	time-averaged
v	of volume equivalent

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