SIZE DISTRIBUTION OF PARTICULATE EMISSIONS FROM A PRESSURIZED FLUIDIZED BED COAL COMBUSTION FACILITY

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Abstract—Particle size distribution measurements were conducted on the emissions from the pressurized fluidized bed coal combustion test facility at the British National Coal Board, Coal Utilization Research Laboratory, Leatherhead England during September 1979. The particle size samples were taken on stream 1 downstream of the third stage cyclone and upstream of the cascade of turbine blades supplied by Stal Laval. The particle size distribution measurements were performed using an 11 stage Mark 5 University of Washington Source Test Cascade Impactor. The mass median aerodynamic particle diameter of the 14 size distribution tests ranged from about 1.6 to 3.4 μm with an average of around 2.5 μm. The geometric standard deviation of the log-normal approximation of the particle size distributions ranged from 2.3 to 3.6. The particle size distributions were very nearly log-normal in shape with the correlation coefficients between the actual and log-normal approximation ranging from 0.98 to 0.998 with an average of 0.992. The particle mass concentrations ranged from 0.39 to 0.69 g m^{-3} at actual conditions (or 0.11 to 0.21 g m^{-3} at standard conditions).

1. INTRODUCTION

(A) *Purpose of paper*

The purpose of this paper is to present the results of the particle size distribution tests conducted at the pressurized fluidized bed coal combustion facility at the British National Coal Board, Coal Utilization Research Laboratory (CURL), Leatherhead, U.K. The particle sizing was conducted with a cascade impactor with the gas pressure at about 506.6 kPa (5 atm.) at the impactor inlet. The gas temperatures were in the 107 to 238°C range. The particle size distribution data are of significance to studies of gas turbine blade life and to the design of hot gas particulate control devices for emissions from pressurized fluidized bed coal combustion facilities.

(B) *Review of literature*

Henschel (1978) reviewed the U.S. developments and the emissions from fluidized bed coal combustion (FBC). He reported that fluidized bed combustors should be able to meet the 1978 U.S. new source performance standards for emissions of SO_2 at 574 kg 10^{-6} joules (1.2 lbs 10^{-6} Btu) and of NO_x at 335 kg 10^{-6} joules (0.7 lb 10^{-6} Btu). However, the ability of FBC to meet new source performance standards for large coal-fired steam generators for particulates of 48 kg 10^{-6} joules (0.1 lbs 10^{-6} Btu) had not yet been demonstrated. The need for final stage particle control equipment after the upstream cyclones with 80–97% collection efficiency for particles of 7 μm mass median diameter was identified.

Murthy *et al.* (1979) reported on the results of comprehensive analyses of gaseous and particulate emissions from a pressurize fluidized bed coal combustion unit (Exxon Miniplant). The particle mass concentration downstream of two cyclones was 2.75 g m^{-3} (1.2 grains scf^{-1}) or 817 kg 10^{-6} joules (1.9 lbs 10^{-6} Btu). The size distribution of these particles was 9% by weight than 1 μm, 39% in the 1–3 μm range, 21% in the 3–10 μm range and 33% greater than 10 μm. About 46% by weight of the particles collected by the source assessment sampling system's cyclone was less than 3 μm and is in the respirable range. They concluded that particulate emission control technology on pressurized coal-burning FBC units needs to be demonstrated.

Hoy and Kaye (1979) reported on the work of the British National Coal Board's research and development of fluidized bed combustion. The British Coal Utilization Research Laboratory (CURL) pressurized fluidized bed coal combustion facility (Leatherhead, England) was used for tests on supplying hot combustion gases to gas turbines. The problem of cleaning the hot gases upstream of the turbine in order to prevent excessive erosion of the turbine blades was studied. Early tests with gases from the pressurized FBC unit passing through two stages of cyclones and then impinging on target metal rods showed that rapid deterioration of turbine blades would most likely occur. No data on the particle mass concentrations or size distributions were provided.

Highley (1980) reviewed the development of fluidized bed combustion by the British National Coal Board. He reported that the pressurized FBC coal-burning technology is nearing the point at which this technology can be demonstrated with a large gas turbine and thus show the high efficiency achievable in a combined cycle power generation. No mention was made of the particulate control equipment to be used to clean the gases upstream of the gas turbine. However, Highley reported that tests with static turbine blade cascades continue to give favorable predictions of acceptable blade life.

(C) *Sampling site*

The particle size distributions measurements were conducted on the pressurized FBC unit at the British National Coal Board's Coal Utilization Research Laboratory, Leatherhead, England in September 1979. Hoy and Kaye (1979) described the pressurized FBC pilot plant and the operating parameters are presented in Table 1.

A schematic diagram of the CURL pressurized FBC unit is shown in Fig. 1. Our particle size measurements were conducted on 'Leg 1', downstream of the tertiary cyclone and upstream of the materials test section.

2. EXPERIMENTAL TECHNIQUES

(A) *Particle sizing instrumentation*

The particle size distribution measurements were performed using a Mark 5 University of Washington Source Test Cascade Impactor. The U. of W. Source Test Cascade Impactors include the models Mark 1 and 2, as described by Pilat *et al.* (1970), the models Mark 3 and 4, as described by Pilat *et al.* (1978) and the Mark 5 which is an eleven stage version of the seven stage Mark 3. The jet stage hole diameters, the numbers of holes per stage, and the aerodynamic cut diameters for the Mark 5 UW Cascade Impactor used in the tests at CURL are presented in Table 2.

The aerodynamic cut diameters da_{50} listed in Table 2 are for a gas sampling flow rate of 14.4 $\ell\,min^{-1}$ (0.51 acfm), temperature of 144°C, and impactor inlet pressure of 529 kPa (156 inches Hg).

A schematic illustration of the cascade impactor sampling train is shown in Fig. 2. A sample gas stream from the FBC exhaust was extracted through an isokinetically designed probe. The cascade impactor was connected directly to the sample probe line. The gas pressure and temperatures at the impactor inlet and outlet were measured and recorded. A 47-mm dia. filter holder was located downstream of the impactor outlet to filter those particles not collected by the cascade impactor. Following the filter, the sampled gases flowed through a condenser unit consisting of Greenburg–Smith impingers in an icebath. From the impingers, the gases flowed to a leakless vacuum pump and on through a dry gas meter.

(B) *Sampling procedure*

Pretest preparations, conducted at the U. of Wash., consisted of insert-substrate preparation and weighing and calculations of the gas sampling flow rates for operation at the 506.6 kPa pressure conditions. The stainless steel foil inserts for the particle collection plates of the impactor were modified to have hold-down tabs to attach the filter substrates, as shown in Fig. 3. The foil inserts were cleaned with acetone in an ultrasonic cleaner. The glass fiber filter substrates (Whatman Reeve Angel 934 AH), precut into a size that fits the impactor collection plate foil inserts, were placed onto the inserts and the tabs bent over to hold the substrates in place. This procedure of using the hold down tabs prevents the filter substrates from becoming dislodged during shipment or testing.

The foil inserts with the filter substrates were placed

Table 1. CURL pressurized FBC operating parameters

Parameter	Range
Coal heat input	1–3 MW
Fluidizing velocity	0.55–2.5 $m\,s^{-1}$
Bed temperature	700–950°C
Excess air	15–300%
Pressure	300–600 kPa
Bed depth	1.25–2.5 m
Tube bank arrangement	vertical and horizontal
Bed cross-section	91 × 61 cm
	123 × 61 cm
Coal ash content	9–60%
Coal rank	low to coking coal
Calcium/sulfur	0–3

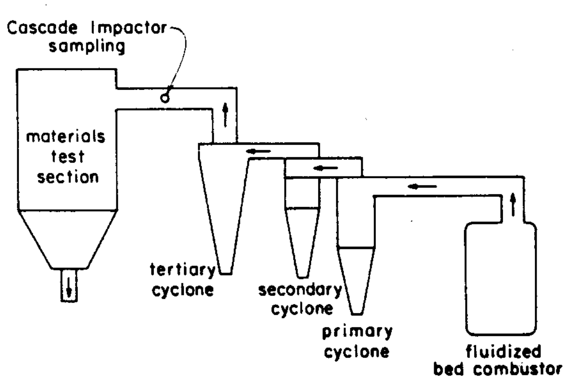

Fig. 1. Diagram of CURL fluidized bed coal combustion facility (Leg 1).

Table 2. Mark 5 UW impactor jet stage characteristics

Stage	No. jets	Jet diameter (inches)	(cm)	da_{50} (μm)
1	1	0.617	1.568	26.57
2	6	0.228	0.580	14.61
3	12	0.110	0.280	6.91
4	90	0.031	0.079	2.81
5	110	0.020	0.051	1.60
6	110	0.0157	0.040	1.10
7	110	0.0135	0.035	0.87
8	105	0.0118	0.030	0.69
9	100	0.0100	0.026	0.52
10	80	0.0094	0.024	0.41
11	70	0.0087	0.022	0.29

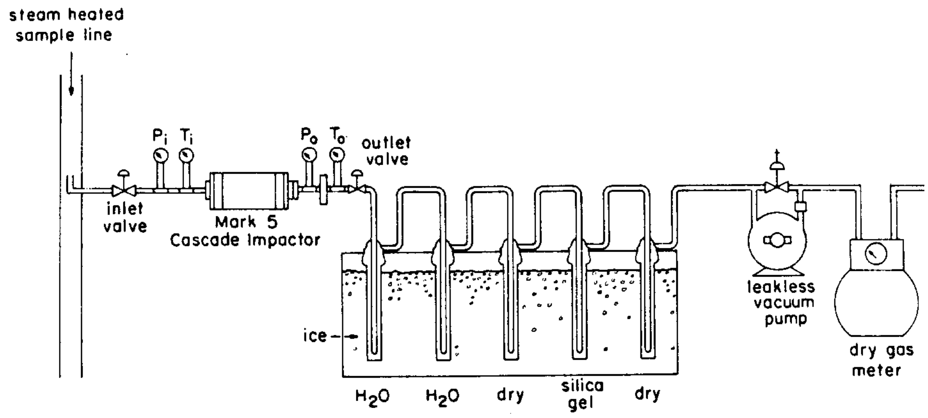

Fig. 2. Mark 5 UW cascade impactor sampling train.

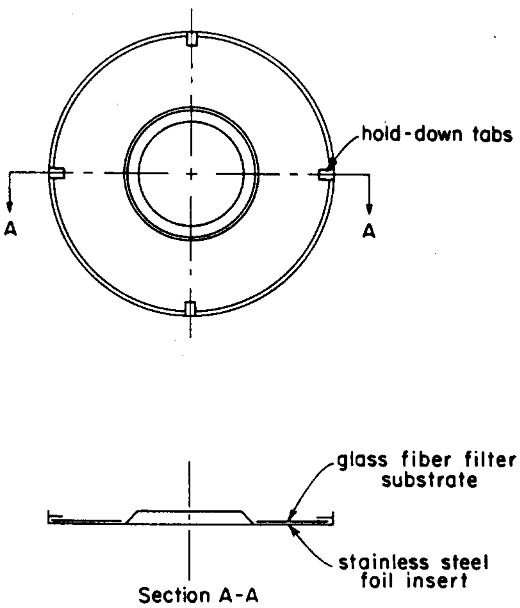

Fig. 3. Collection plate inserts with glass fiber substrates.

in Pyrex glass petri dishes, baked at 288°C for 4 h cooled in a desiccator for 12 h, and weighed on a type 86 Mettler balance. The inserts plus substrates were then placed in labeled plastic petri dishes for shipment to the test site.

At CURL, the impactor sampling train was set up as shown in Fig. 2. The impingers were prepared for each test with about 100 ml of water in impingers 1 and 2, impinger 3 was empty, impinger 4 contained about 150 grams of fresh silica gel and impinger 5 was empty. All five impingers were weighed before and after each test. The Cascade Impactor was wrapped in glass wool insulation and preheated to 260°C in an oven for 30 min. The hot Impactor was connected to the sampling train and leak checked. Prior to each test, the sampling lines were purged with nitrogen gas to remove any dust which may have accumulated on the duct walls, valves, etc. With the Impactor connected to the sampling line, the inlet valve was fully opened and the Impactor brought up to duct pressure. The vacuum pump was then started and the valve downstream of the Impactor opened to such a position so that with a predetermined Impactor outlet pressure (in the 318–352 kPa range), the gas flow rate through the Impactor was in the 11–14 $\ell\,\mathrm{min}^{-1}$ range and provided the desired aerodynamic cut diameters. Care was taken to adjust the impactor outlet valve and the pump flow rate to prevent blowing the tops off of the impingers (impingers need to be operated under vacuum conditions). Sampling times ranged from 8–30 min. With these operating conditions about 70 % by weight of the particles were collected on the plates under jet stages 3, 4, 5 and 6 (in the 1–8 μm dia. range).

After each test the hot Impactor and the condenser unit was transported to the laboratory at the CURL facility and dismantled. The insert-substrates with the particle samples were placed in the labeled plastic petri dishes and shipped back to the U. of Wash. lab where they were baked at 121°C for 2 h, cooled and weighed on the same Mettler balance.

(D) *Data analysis*

The analyses of the Impactor data into particle size distributions included calculations of the gas pressure on each of the Impactor stages, calculation of the stage da_{50}s, and processing the data into distribution curves. The Impactor inlet and outlet pressures, gas temperature, jet stage hole diameters, number of holes per stage, gas flow rates, etc. were used in a computer program (TESTER) to calculate the absolute gas pressures on each stage. The calculated absolute gas pressures along with the field and lab data were used in another computer program (RASS) to calculate the stage da_{50}s and the weight cumulative and $dM/d\log D$ size distribution curves. The particle cut diameter d_{50} of the Impactor stage was calculated with the equation

$$d_{50} = \left[\frac{18\,\mu D_j \psi_{50}}{C \rho_p V_j}\right]^{\frac{1}{2}},$$

where μ is the gas viscosity, D_j the jet diameter, ψ_{50} the magnitude of the inertial impaction parameter, C the Cunningham slip correction factor, ρ_p the particle density and V_j the gas velocity in the jet. A particle density of 1.0 g cm^{-3} was used to provide the aerodynamic cut diameter da_{50}.

3. RESULTS

The results of the 14 cascade impactor tests at CURL are presented in Table 3. The test conditions included the gas temperature, gas pressure at the impactor inlet and outlet and gas flow rate through the impactor at actual conditions (actual ℓ min^{-1}). The particle mass concentration is given in actual and standard (20°C and 1 atmosphere pressure) conditions. The geometric standard deviations of the log-normal approximations of the particle size distribution varied from 2.3 to 3.6. The correlation coefficient of the log-normal straight line approximations of the actual distributions ranged from 0.980 to 0.998 and indicates that the distributions were nearly log-normal.

The cumulative particle size distributions of the 14 tests are shown in Fig. 4. The mass median diameters for the actual distributions ranged from about 1.6 to 3.4 μm. The differential particle size distributions are shown in Fig. 5. In general the curves have a peak in the 2 μm dia. range.

A composite curve for the 14 tests at CURL and a size distribution reported by Murthy *et al.* (1979) for the Exxon pressurized Miniplant are presented in Fig. 6. The mass median diameters of 2.5 μm for CURL and 3.8 μm for the Exxon Miniplant compare reasonably well. The Exxon size distribution appears to be somewhat more polydisperse, however, this may be the result of only three data points being available.

Table 3. Results of Impactor tests at CURL FBC unit

Test No.	Impactor temp. (°C)	Press (kPa) in	Press (kPa) out	Gas flow ℓ min^{-1}	Water vapor (%)	Particle mass conc. Actual ($g\,m^{-3}$)	Particle mass conc. Standard ($g\,m^{-3}$)	Log-Normal st. line approximation Mean dia. (μm)	Geo. S.D.	Corr. coef.
2	121	420	345	11.0	3.6	0.41	0.110	3.0	2.5	0.980
3	121	420	345	11.9	3.8	0.39	0.107	2.5	2.7	0.990
4	132	420	352	11.3	3.9	0.41	0.114	3.2	2.6	0.990
5	124	427	352	11.9	3.9	0.41	0.112	3.6	2.3	0.991
6	144	427	318	14.4	4.1	0.50	0.142	3.1	2.6	0.991
7	126	427	318	13.8	3.6	0.57	0.153	3.1	2.7	0.997
8	118	413	318	14.2	3.5	0.57	0.151	2.3	3.6	0.998
9	117	427	318	14.2	3.5	0.55	0.146	2.9	3.0	0.997
10	161	423	322	15.3	1.6	0.48	0.140	3.0	2.7	0.993
11	113	423	322	12.2	2.6	0.69	0.176	3.1	3.0	0.995
12	238	413	325	15.0	3.1	0.43	0.149	2.4	2.7	0.990
13	107	413	332	10.5	2.1	0.59	0.156	3.8	3.0	0.998
14	135	406	325	12.5	3.3	0.57	0.162	2.8	2.9	0.997
15	179	410	332	9.9	4.1	0.66	0.213	3.2	2.8	0.987

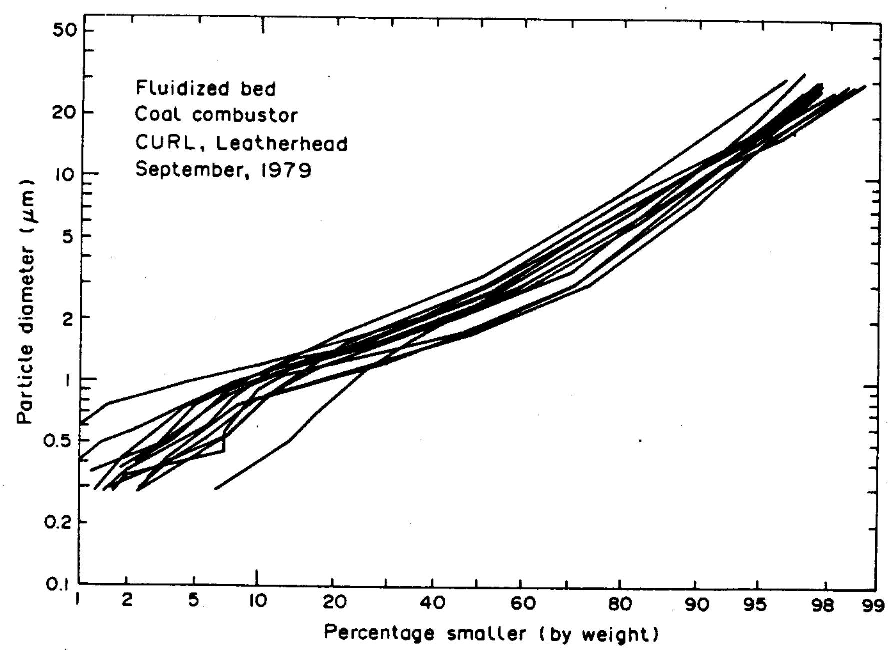

Fig. 4. Cumulative particle size distributions.

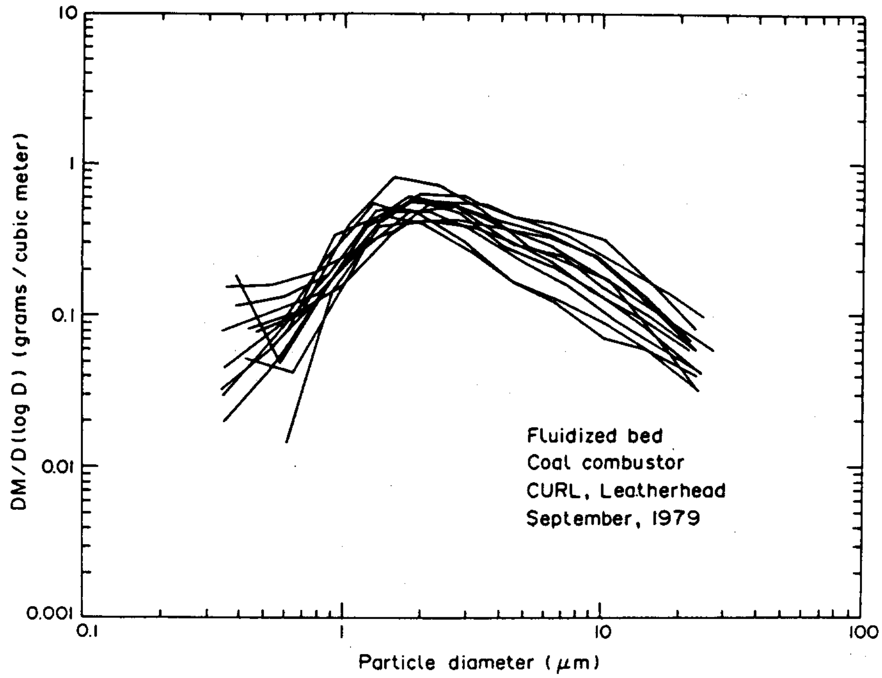

Fig. 5. Differential particle size distributions.

4. CONCLUSIONS

The particle size distribution tests at the pressurized fluidized bed coal combustion facility at CURL, Leatherhead, England, show the mass mean particle diameter in the 1.6–3.4 μm range and the particle mass concentration in 0.39–0.69 g m^{-3} actual conditions (0.17–0.30 grains/acf).

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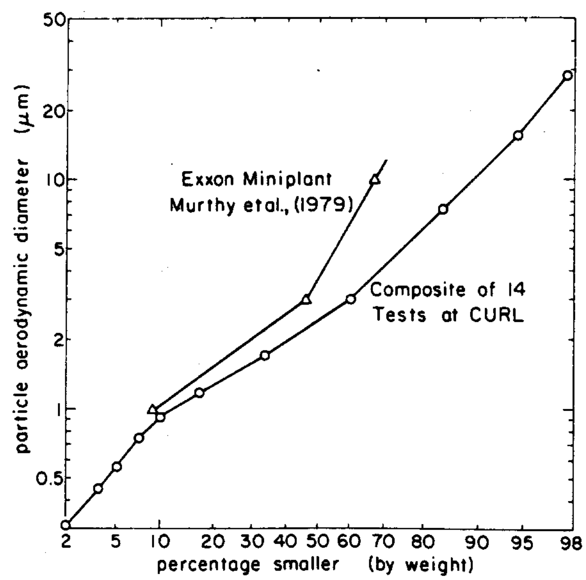

Fig. 6. Particle size distributions from CURL and Exxon FBC units.

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