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The Shape Factors of Coals Ground in a Standard Hardgrove Mill

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The shape factors of 16 coals of various rank were determined, after the coals had been ground according to the standard A.S.T.M. Hardgrove test. The shape factor was found to be constant with size for a given coal over the size range tested, 16 to 325 mesh. Shape factors were found to be a function of coal rank. A graphical correlation of shape factor with volatile matter is given.

THE shape factor of ground coals is an important parameter where pressure drops through packed or fluidized beds of fine coal have to be calculated[1-3]. In addition, the envelope surface areas of a coal sample can be calculated from its size distribution and shape factor. This is of importance in such processes as the combustion and gasification of pulverized coal, the production of low temperature coke and coal chemicals by fluidized bed techniques, and the transport of coal in fluid suspension. The surface area of coal has received much study in connection with grinding[4]. In the present work, the shape factors of 16 coals of varying rank were determined, after the coals had been ground according to the standard A.S.T.M. Hardgrove test.

DEFINITION OF SHAPE FACTOR

The shape factor ϕ is defined by

$$S_0 = 6/\phi\mu \qquad \ldots.[1]$$

where S_0 is the specific area (area per unit volume) of the particles and μ is the sieve size of the particles. A sphere or cube gives a shape factor of 1, while more flaky or needle-like particles give lower shape factors. If ϕ and the size distribution are known, then S_0 for a collection of different sized particles can be calculated from

$$S_0 = \int_0^1 (6\rho/\phi\mu)\,\mathrm{d}w \Big/ \int_0^1 \rho\,\mathrm{d}w \qquad \ldots.[2]$$

where dw is the fractional weight of particles of size μ and ρ is the apparent density of the particles.

APPARATUS AND EXPERIMENTAL TECHNIQUE

The coal was ground in a Hardgrove test machine according to the A.S.T.M. standard method[5]. The product was sieved into the following fractions: 16 × 30, 30 × 35, 35 × 50, 50 × 70, 70 × 100, 100 × 120, 120 × 140, 140 × 170, 170 × 200, 200 × 230, 230 × 325, U.S. mesh. These fractions were used for the density and surface area measurements described below.

The surface areas of the coal fractions were determined using the liquid permeability apparatus described by M. L. LAKHANPAL, V. D. ANAND and B. R. PURI[6]. The method was simple and quick and gave fairly good reproducibility. The major difficulty arose in obtaining a bed free from air bubbles. When air was present, the bed had a characteristic mottled appearance at the surface of the tube and surface areas were both too high and poorly reproducible. This difficulty was overcome by allowing the coal sample to soak in boiled-out water for an hour before use, with frequent stirring. If the coal was well wetted and packed under suction (from a water pump) with a continuous flow of boiled-out water, air bubbles were not found in the bed.

To measure the surface area by the permeability method, it was necessary to know the apparent density of the coal particles tested as a function of particle size. Apparent densities were determined using a mercury porosimeter[7]. The pressure of mercury was increased until the rate of entry of mercury dropped suddenly and additional pressure caused only a small further penetration. The sudden change-point was taken as equivalent to the apparent (geometric) density and the slow additional penetration as the filling of the internal pore system of the particles. It was found that a pressure of 60 lb/in^2 gauge was sufficient to force the mercury between the particles of the finest coal used, while increasing the pressure to 200 lb/in^2 gauge produced an insignificant change in penetration. Densities of the larger sieve sizes, determined by rapid water displacement, agreed with the mercury densities.

The specific surface area of a coal fraction was calculated from the following formula, which applies to the permeability apparatus used.

$$S_0 = \frac{(6)(10^4)}{5[k_0q^2/4]^{\frac{1}{2}}[R_1/R][(1-\epsilon)/\epsilon][10^5(\eta L/\epsilon t)\log(l_2/l_1)]^{\frac{1}{2}}} \qquad \ldots.[3]$$

k_0q^2 is a factor which varies with the shape of the pores in the bed, R is the radius of the tube containing the bed, R_1 is the radius of the tube in which the mercury rises, ϵ is the porosity of the packed bed, η is the viscosity, L is the length of the packed bed, l_2 and l_1 are the pressure differentials across the bed initially and finally, and t is the time of flow. Recommended values for the factor k_0q^2 are 4·0 for circular pores, 4·8 for a bed composed of spheres, and 5·0 for a bed composed of irregular particles[8]. (It may be noted that the denominator on the RHS of equation 3 is the surface-area-per-unit-volume equivalent diameter, in microns if c.g.s. units are used.) The latter value was used for the present calculations on coal. Curves of cumulative area versus sieve size were compiled and values of S_0 at given values of μ were used to calculate ϕ, using equation 1. Alternatively, ϕ was calculated, for a narrow sieve range, from the relation $\phi = 6/S_0\bar{\mu}$, where $\bar{\mu}$ is the arithmetic mean of the sieve range.

The liquid permeability apparatus was tested by using it to measure the surface area of a sample of glass spheres of size 100 to 200 microns, the glass having a density of 2·50 g/cm^3. In addition, a microscope size count was made on the spheres and the surface area calculated by integrating the range of sizes present. The permeability area agreed to within ±5 per cent for six tests, and the mean of the six tests gave an area which agreed with the microscope-count area within 1 per cent.

RESULTS AND DISCUSSION

Table 1 gives the analyses of the coals used in the tests, the Hardgrove grindability index, and the shape factor for the coals. The shape factor was found to be constant, within the limits of experimental error (±10 per cent of the mean), for different sizes of the same coal over the size range tested (16 to 325 mesh). Each shape factor is the mean of at least 15 different packed columns of coal.

Table 1. Results on coals tested

Coal	*State*	*Composition on as-received basis, wt %* H_2O	*Ash*	C	H	S	*% Volatile matter (d.a.f.)*	*Hardgrove grindability index*	*Shape factor* ϕ
St Nicholas	*Pa*	1·6	9·1	84·2	2·4	0·51	4·5	30	0·64
Lorree Raven	*Pa*	4·0	7·1	82·7	2·8	0·80	5·4	26	0·61
Dorrance	*Pa*	0·7	9·9	82·9	2·5	0·73	5·8	29	0·59
Treverton	*Pa*	0·5	9·7	—	—	1·05	9·0	51	0·69
U. Freeport	*Md*	0·5	14·4	75·2	3·9	1·75	17·9	99	0·83
U. Kittanning	*Pa*	0·5	9·5	80·4	4·2	1·46	18·0	102	0·78
Pratt	*Ala.*	0·8	7·9	78·8	4·8	1·60	29·2	93	0·75
L. Kittanning	*Pa*	0·5	11·0	76·8	4·9	1·62	30·2	97	0·71
U. Freeport	*Pa*	0·4	7·9	79·8	5·0	1·59	33·0	84	0·70
Cobb	*Ala.*	1·5	6·7	77·1	5·1	1·22	33·1	63	0·68
Pittsburgh	*Pa*	1·1	5·6	77·5	5·3	1·50	37·4	54	0·65
Glen Mary	*Tenn.*	2·1	7·5	72·7	5·3	2·76	39·4	55	0·68
Pittsburgh	*Pa*	1·4	6·6	76·2	5·4	2·22	39·5	53	0·65
Pittsburgh	*Pa*	1·4	5·3	77·3	5·4	1·81	40·0	52	0·62
Pittsburgh 8	*Ohio*	1·5	16·4	65·5	4·9	4·51	42·4	52	0·62
No. 6	*Ill.*	1·9	7·6	66·1	5·5	2·75	45·4	55	0·62

Figure 1 shows the relation between shape factor and volatile matter. Using this curve the shape factor can be estimated from the volatile matter with an accuracy of within ±10 per cent.

As described, the surface areas were obtained by a liquid permeability method, using closely sized fractions, with a minimum size of 325 mesh (44 microns). Consequently, the well-known disadvantages of air permeability techniques are not involved. The mean free path of the liquid molecules is not great enough compared with the pore radii for slip phenomena to be significant. Flow is laminar at all times and the rates of flow are much too low for expansion-contraction losses to be appreciable. The difficulties of testing fine powders (less than 5 microns) by permeability techniques were also not encountered in this work. On the other hand, one step in equation 3 involves converting the Poiseuille equation for a tube into the equation for a packed bed by substituting an overall mean hydraulic radius [defined by $\epsilon/(S_0)(1-\epsilon)$]. This is only justifiable when the pores in the packed bed have a uniform shape and size. For a range of shapes and sizes, the true overall mean hydraulic radius is an appropriate integration of the distribution of hydraulic radii. The term k_0q^2 in equation 3 contains a correction factor to allow for this non-ideality of the pore system; k_0q^2 is a constant for a given bed. However, it is to be expected that k_0q^2 will vary depending on the packing of the bed. In the work reported here, the porosities of the packed beds were within the range 0·4 to 0·6. Therefore, the variation of k_0q^2 associated with consolidated beds or highly porous beds should not be encountered. For similar conditions, P. C. CARMAN[9] quotes a variability of k_0q^2 equivalent to ± 14 per cent. When the reverse process is carried out, that is, a mean value of k_0q^2 is assumed and S_0 calculated, it is obvious that a similar spread in values of S_0 will be encountered. In the work reported here, the reproducibility of results on the same bed, but with different pressure drops, time of flow, etc., was normally within ± 1 per cent. The reproducibility of S_0 on different beds of the same material was normally within ± 10 per cent. Since $S_0 \propto 1/(k_0q^2)^{\frac{1}{2}}$, the order of reproducibility expected from the range of k_0q^2 values quoted above is ± 8 per cent. At least 15 different beds were tested for each coal; therefore, the mean shape factors are probably good to within ± 3 per cent.

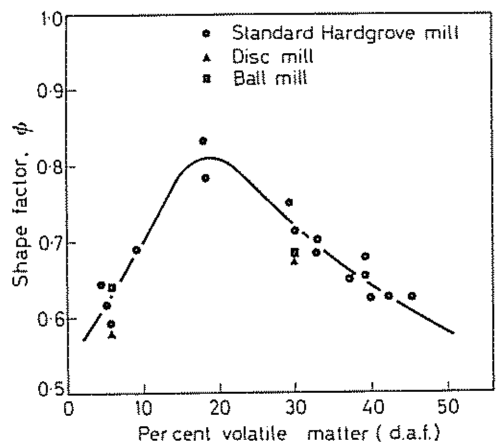

Figure 1. Relation between shape factor, ϕ, and the percentage of volatile matter (d.a.f.) of coals

Without a direct calibration of the permeability area versus the geometric area, using some other means of area determination, it is not possible to say how accurate are the shape factors measured. Indeed, the area of a sample will vary depending on how the area is measured. The liquid permeability technique used here will measure none of the internal surface area of the coal and little if any surface roughness. The shape factors obtained using a value of 5 for k_0q^2 are probably reasonably good guides to the geometric surface area for drag or mass transport of a reactant to the surface and they should be directly comparable between different coals. They do not give any indication of the variation of shape of individual particles within a given sample.

It appears unlikely that the shape factor is a function of the degree of grinding (at least, over the size range investigated). If it were, the factor would be expected to vary for different sized fractions because the finer fractions contain material which has been broken several times.

Two coals were also ground in a disc mill and in a ball mill. Although the shape factors found were significantly different from those of the same coals ground in the standard Hardgrove machine, the results could still be predicted within ± 10 per cent from *Figure 1*.

CONCLUSIONS

The geometric or hydrodynamic area obtained with the liquid permeability apparatus should not be a function of the chemical nature or roughness of the particle surface, since the resistance to flow is due to the internal friction of the liquid. Consequently, the variation of shape factor implies that coals fracture to different mean shapes depending on their rank. The results indicate that bituminous coals with volatile matter of 15 to 25 per cent (d.a.f.) have the most cubical shapes, while higher and lower rank coals have less cubical breakage products.

It is concluded that shape factor can be added to the list of coal properties which are rank dependent, having a maximum in the region of 15 to 25 per cent volatile matter and minimum values for anthracites and sub-bituminous coals.

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REFERENCES

[1] PERRY, J. H. *Chemical Engineers' Handbook*, 3rd ed., p 394. McGraw-Hill: New York, 1950

[2] CARMAN, P. C. *Trans. Instn chem. Engrs, Lond.* 1937, **15**, 150

[3] ERGUN, S. and ORNING, A. A. *Industr. Engng Chem. (Industr.)*, 1949, **41**, 1179

[4] *Crushing and Grinding Bibliography*. Department of Scientific and Industrial Research; Her Majesty's Stationery Office: London, 1958

[5] *Grindability of Coal by the Hardgrove Method*. American Society Testing Materials *Standard D490–51*

[6] LAKHANPAL, M. L., ANAND, V. D. and PURI, B. R. *Nature, Lond.* 1955, **176**, 692

[7] ANDERSON, R. B., HALL, W. K., LECKY, J. A. and STEIN, K. C. *J. phys. Chem.* 1956, **60**, 1548

[8] CARMAN, P. C. *Flow of Gases through Porous Media*, p 36. Academic Press: New York, 1956

[9] CARMAN, P. C. *Flow of Gases through Porous Media*, p 14. Academic Press: New York, 1956

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