STUDIES ON FLUIDISATION OF PAKISTAN COALS: SOME EFFECTS OF SIZE OF PARTICLES AND VISCOSITY, DENSITY AND VELOCITY OF GAS

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Experiments in tubes up to 5.5 inches in diameter have been carried out with a number of gases to examine the factors which determine the state of fluidisation of beds of coal and the gas velocities required to fluidise beds of particles of various sizes within the range -10+100 B.S. mesh. The linear gas velocity required has been found to be inversely proportional to the absolute viscosity of the gas and independent of its density. It is proportional to the density of the solid. Though a definite relationship between fluidising and critical velocity is not proposed, the results indicated that any such relationship must take particle size into account.

Introduction

In connection with studies of Pakistan coals, it was considered necessary to examine the effect of different gases on coal in a fluidised condition instead of a static bed condition. In spite of certain disadvantages the fluidised bed technique, for reaction between solid particles and gases, seems to offer several advantages over static bed methods which include high heat and mass transfer rates, ability to treat coal fines, ease of solids handling, high output per unit of reaction space and saving in capital. This is an important consideration in connection with the economic utilisation of the indigenous coal and resources of the country on industrial scale. It was assumed that fluidised fuel beds used on large scale would be at least 6 ft in depth and at high temperature. The fluidising gas would be air or steam passing upwards at a velocity of approximately 1 ft per sec at the reaction temperature. Lower velocities would give too low rates of gasification.

The coals were available as irregular particles of all sizes up to 3/16 inches but could be crushed to smaller sizes. This paper describes the experiments which were carried out with the object of examining the separate effects of a number of variables.

The principal variables could be the particle size, size distribution, density and shape factor, the velocity, density and viscosity of the gas, and the diameter and depth of the bed. Some of these were examined in the present work, including size range rather than size distribution.

Experimental

Four different indigenous coal samples from Makarwal, Deghari, Sharig and Sor Range areas in West Pakistan, having specific gravities between 1.3 and 1.6, were used. The coal particles were contained in Perspex tubes of sizes from 2.4 in to 5.5 in internal diameters with an inlet for the fluid. A cotton disc was placed at the top of the conical base so that the cross section remained constant. The apparatus is shown in Fig. 1. In these experiments, air, hydrogen and the Sui gas (consisting of 95% methane) were utilised.

The fluidising gases were supplied both by compressor and gas cylinders, depending on the rate of gas required for each series of experiments. The gases were admitted at the base of the column through the cotton disc, resting on wire-gauze of 300 mesh B.S.S., and their rates were measured with rotameters and also with wet and dry displacement meters.

In each experiment a known weight of sample, which was already dried at 105±2°C, was placed in the Perspex tube and the gas was passed with such an increasing rate that fluidising conditions were obtained. For each run, the difference between the gas pressure above the bed and at a point 0.5 in above the base of the bed was measured. All the coal samples were crushed and screened to have the sizes as shown in Table 1.

The specific gravities of each size fraction of each coal were measured and are shown in Table 2, and the densities and viscosities of the gases used are shown in Table 3.

Results and Observations

With gradual increase in the gas velocity from zero there was a progressive change of pressure as shown in Figs. 2, 3 and 4 for −36+72 mesh Makarwal coal.

The increase in pressure drop was in a linear manner with increasing rate of gas velocity up to the point A without any obvious movements of the coal particles. With slight increase in the velocity of gas there was light movement of the particles with the consequent increase in the pressure drop up to the point B and then the pressure drop decreased slightly. At point B, the bed started "boiling" indicating incipient fluidisation. There was no further increase in pressure drop though the gas velocity was further increased. The bed was still fluidising more vigourously while its volume kept on increasing.

Although there is no method available for establishing precise fluidising conditions in the sense of being technically satisfactory, it was observed that good mixing of the particles and circulation of fluidising medium could be maintained when the gas velocity was 2 to 8 times that corresponding to the point B. This factor increased with decreasing particle size.

The behaviour in the different regions of the curves can be described as follows:

OA	A straight line over which range the bed is in a static condition and the void fraction is more or less constant.
AB	A region over which the bed fluidises, starting at the top A and progressing down the bed to B. As more of the bed becomes fluidised, the pressure drop curve falls away from the linear range to approach a value equal to bed weight per unit area.
BC	A line showing the bed fully fluidised and becoming more and more violently agitated as the gas rate flow is increased.
CD	A slugging region in which pressure drop may oscillate violently. The critical velocity (V_c) was defined as that obtained graphically by extrapolating the linear parts of the curve OA and CB′ at B′. The final pressure drop ΔP_f through the fluidised bed was in agreement with the "hydrostatic" head (ΔP_h) calculated from the weight of solids and the cross-section of the tubes, as shown in Table 4.

The curves representing the pressure drop through static beds as a function of gas velocity up to the critical velocity were found to agree with Kozeny's relation (1) as modified by Leva.[1]

$$\frac{\Delta P}{L} = \frac{KG\eta}{\rho D_p{}^2 g} \cdot \frac{\lambda^2(1-\delta)^2}{\delta^3} \qquad (1)$$

where L, D_p, G, η, ρ and δ are respectively the depth of bed, particle diameter, mass velocity of gas per unit cross-section for empty tube, absolute viscosity and density of gas, and void fraction in the bed. λ is a shape factor which is unity for spheres.[2] The constant K is 200 in the ft-lb-hr system of units.

The shape factor was determined from all the data obtained in the region OA with each coal, each particle size and each gas, by plotting values of log f against values of log Re in Fig. 5, where f, the friction factor is given by:

$$f = (\Delta P D_p \rho g \delta^3) / (2G^2 L (1-\delta)^2)$$

and where Re, the Reynolds Number is given by:

$$\mathrm{Re} = GD_p/\eta$$

A straight line of slope -1 has been drawn through the points in Fig. 5, this line corresponds with the equation

$$\log f = \log(100\lambda^2/\mathrm{Re})$$

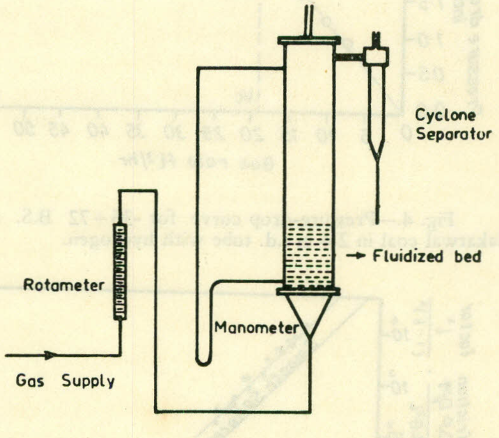

FIG. 1

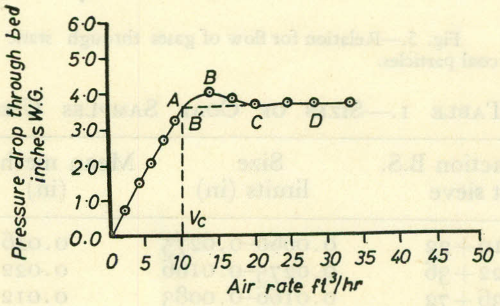

Fig. 2.—Pressure-drop curve for -36+72 B.S. mesh Makarwal coal in 2.4 in i.d. tube with air.

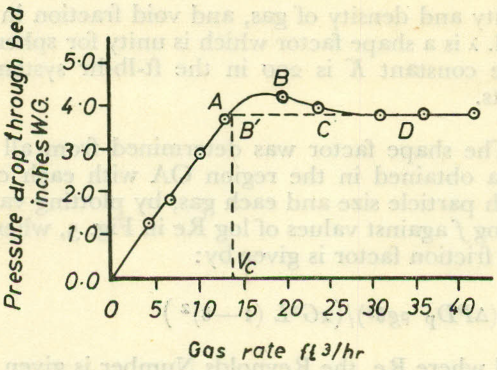

Fig. 3.—Pressure-drop curve for -36+72 B.S., mesh Makarwal coal in 2.4 in i.d. tube with Sui gas.

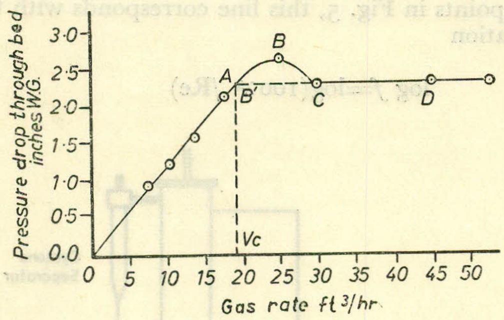

Fig. 4.—Pressure-drop curve for -36+72 B.S. mesh Makarwal coal in 2.4 in i.d. tube with hydrogen.

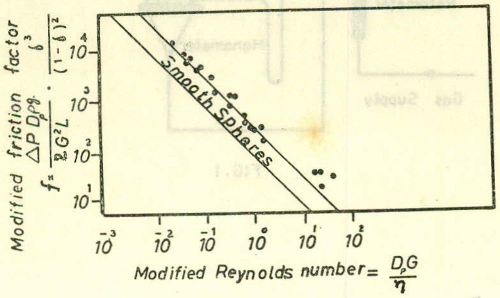

Fig. 5.—Relation for flow of gases through static beds of coal particles.

TABLE I.—SIZES OF COAL SAMPLES USED.

Fraction B.S. test sieve	Size limits (in)	Mean mesh size (in)
−10+22	0.0660–0.0275	0.046
−22+36	0.0275–0.0166	0.022
−36+72	0.0166–0.0083	0.012
−72+100	0.0083–0.0060	0.007

TABLE 2.—SPECIFIC GRAVITIES OF COAL SAMPLES USED.

Fraction B.S. test sieve	Makarwal	Deghari	Sor range	Sharig
−10+22	1.620	1.360	1.350	1.300
−22+36	1.570	1.360	1.365	1.302
−36+72	1.540	1.360	1.370	1.307
−72+100	1.500	1.370	1.380	1.300

TABLE 3.—PROPERTIES OF GASES USED AT STANDARD CONDITIONS. (0°C, 1 atm).

Gas	Density lb/ft³	Viscosity lb/hr/ft
Air	0.0808	0.04114
Sui gas	0.0448 (approx)	0.02395 (approx)
Hydrogen	0.0056	0.02057

TABLE 4.—COMPARISON OF OBSERVED AND CALCULATED PRESSURE DROP THROUGH FLUIDISED BED FOR AIR.

Particle size range (B.S. mesh)	Values of $\Delta P_f/\Delta P_h$			
	Makarwal	Deghari	Sharig	Sor range
−10+22	0.910	0.900	0.929	0.965
−22+36	0.915	0.946	0.926	0.967
−36+72	0.933	0.956	0.917	0.982
−72+100	0.928	0.937	0.932	0.971

which is an alternative version of the Kozeny's equation. The value of λ deduced from Fig. 5 was 1.95. Figure 5 also shows the line for smooth spheres

$$\log f = \log(100/\mathrm{Re}).$$

for which the value of λ is unity.

The pressure drop in the fluidised bed equals the weight of material per unit cross sectional area; hence theoretically the critical velocity V_c, is the velocity at which $\Delta P/L$ in the Kozeny's equation can be replaced by $(W/A)/L$ where W is the weight of material, A is the cross sectional area. The value of $(W/A)/L$ is the bulk density, i.e. weight of material per unit volume of bed, which is equal to the density of a particle times the fraction of bed volume occupied by solids, $(1-\delta)$. Hence the Kozeny's equation is written in the form:

$$P_s(1-\delta) = K\, G\, \eta\, \lambda^2 \quad (1-\delta)^2/\rho D_p^2 g \delta^3$$

TABLE 5.—CRITICAL AND FLUIDISING AIR VELOCITIES FOR COAL PARTICLES.
Velocities in ft/sec at 90°F and 14.7 lb/in².

Coal	Mesh B.S. Test Sieve	Size range in	V_c (exp)	V_c (calc)	V_f	V_{25}
Makarwal	−10+ 22	0.0660–0.0275	1.170	1.360	2.570	2.340
	−22+ 36	0.0275–0.0166	0.315	0.326	0.880	0.787
	−36+ 72	0.0166–0.0083	0.089	0.095	0.338	0.311
	−72+100	0.0083–0.0060	0.035	0.034	0.246	0.239
Deghari	−10+ 22	0.0660–0.0275	1.240	1.130	2.480	2.230
	−22+ 36	0.0275–0.0166	0.304	0.310	0.851	0.790
	−36+ 72	0.0166–0.0083	0.098	0.097	0.314	0.294
	−72+100	0.0083–0.0060	0.035	0.031	0.190	0.183
Sharig	−10+ 22	0.0660–0.0275	1.220	1.082	2.680	2.440
	−22+ 36	0.0275–0.0166	0.274	0.265	0.739	0.685
	−36+ 72	0.0166–0.0083	0.088	0.081	0.270	0.424
	−72+100	0.0083–0.0060	0.033	0.029	0.165	0.158
Sor range	−10+ 22	0.0660–0.0275	1.150	1.112	2.300	2.180
	−22+ 36	0.0275–0.0166	0.230	0.270	0.690	0.667
	−36+ 72	0.0166–0.0083	0.092	0.085	0.285	0.276
	−72+100	0.0083–0.0060	0.035	0.031	0.181	0.174

This can be simplified and rearranged to the following form which allows the critical linear velocity, V_c, to be predicted for any particle size and for any gas:

$$V_c = (\rho_s D_p^2 g \delta^3)/(\eta K \lambda^2 (1-\delta))$$

In Table 5 the experimentally observed values of V_c are compared with those calculated from the above equation; it can be seen that satisfactory agreement was obtained. Table 5 also shows fluidising linear gas velocities (V_{25}) which give a 25% expansion of the bed in comparison with its close-packed volume and the velocities (V_f) required to give satisfactory fluidisation.

The agreement between the pressure drop in a static bed and the modified Kozeny's equation means that the critical gas velocity, V_c at any desired temperature and pressure can be calculated from the physical characteristics of the particles and the gas, because the corresponding value of ΔP is given by the weight of the bed divided by the cross section of the tube.[3] If the gas velocity V_f required to give satisfactory fluidisation is simply related to V_c it can then be calculated. Further, the velocity required for fluidisation of a given material at room temperature and pressure can be used to calculate the appropriate velocity for a different gas at a different temperature and pressure on the basis of the effects of gas density and viscosity.[4] It thus appears that good fluidisation is obtained when the bed is expanded to slightly more than 125% of its close-packed volume.

Observations and Conclusions

It was noticed that there are variations in density of coal fractions. Such variations can be attributed not only to the effect of porosity but also to variations in concentration of mineral matter.

As a rule, the mineral matter tends to concentrate in the finer fractions of crushed coal, but sometimes the reverse is true; this may account for the higher density of the coarse fractions of Makarwal coal.

The quality of the fluidisation was better with shallow than with deep beds.

Good fluidisation is obtained when the bed is expanded to more than 125% of its close-packed volume.

The experiment also indicated that critical and fluidising velocities are independent of bed height and are lower in larger diameter vessels in which the walls have a relatively larger effect and prevent fluidisation until a higher velocity has been reached.

7

The maximum bed height which could be used without slugging was about four times the diameter of the tube. Slugging also occurred if the tube diameter was less than about twenty particle diameters.

The main conclusions from the data are as follows: (i) The critical linear gas velocity is inversely proportional to the absolute viscosity and independent of the density of the gas. (ii) The critical linear gas velocity is proportional to the true density of the particles. (iii) The velocity for satisfactory fluidisation exceeds the critical velocity by a factor which increases with decreasing particle size.

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References

1. M. Leva, Chem. Eng. Progr., **43**, 549 (1947)
2. J.H. Perry, Chem. Eng. HandBook (Mc-Graw-Hill, New York, 1950) p, 394.
3. L.J. Jolley and J.E., Stantan, J. Appl. Chemistry, **2**, Suppl. 1, pp. S62–S63, 1952.
4. Spiers, *Technical Data on Fuel.* British National Committee, World Power Conference.