A STUDY ON 'STATIC' FLUIDIZATION

Shabbir Ahmed Qureshi and Salim Reza

Engineering Division, Central Laboratories, Pakistan Council of Scientific and Industrial Research, Karachi

(Received December 10, 1964)

Of all the variables which affect the onset of fluidization, the particle size, the true-density and the viscosity of the material and the fluidizing agent, are the most important. The present investigation relates to the study of these variables with reference to the 'static-fluidization' (defined later), for both the vesicular and non-vesicular materials, such as coal, coke, bentonite, sand, limestone, felspar, and iron-ore, over a wide particle size spectrum namely −10+12, −16+18, −30+36, −60+72, −85+100, −120+150, −150+170, −170+200 mesh B. S. S., using air as fluidizing agent. It has been shown graphically that the pressure drop, ΔP, across the bed is related to the modified Reynolds' number Re′ and is influenced by the particle size. Re′ is shown proportional to dp^2, and a function of the density and voids of the materials used. No correlation is given.

Introduction

When compressed air is passed through a granular bed supported either on a porous plate or a wire screen, (Fig. 1(a)), the bed begins to expand in proportion to the air-rates and a stage is reached when further increase in air-rates brings about particulate motion. Fluidization can thus be split up into two stages. The first stage, where the bed expansion is maximum but no particulate motion takes place, may be termed as 'static-fluidization' (Fig. 1(b)). The second stage, where the whole bed is in a turbulent state and the granules move in a manner as shown in Fig. 1(c), may be called 'dynamic fluidization'. In between the 'static' and 'dynamic' fluidizations, there appears to exist a 'transitional' stage when a part of the bed is in motion while the remaining part is stationary. The present work is restricted to the experimental study of the variables such as pressure drop across the bed, the particle size and its density and finally the voids as function of the air-rates, under 'static' fluidization. It appears though the density considerably affects the value of Re′, but the particle size plays an important role in the study of the variables involved.

Leva, Grummer, Weintraub and Pollchik[1] developed a co-relation for the fluidization of small particles, using non-vesicular materials namely

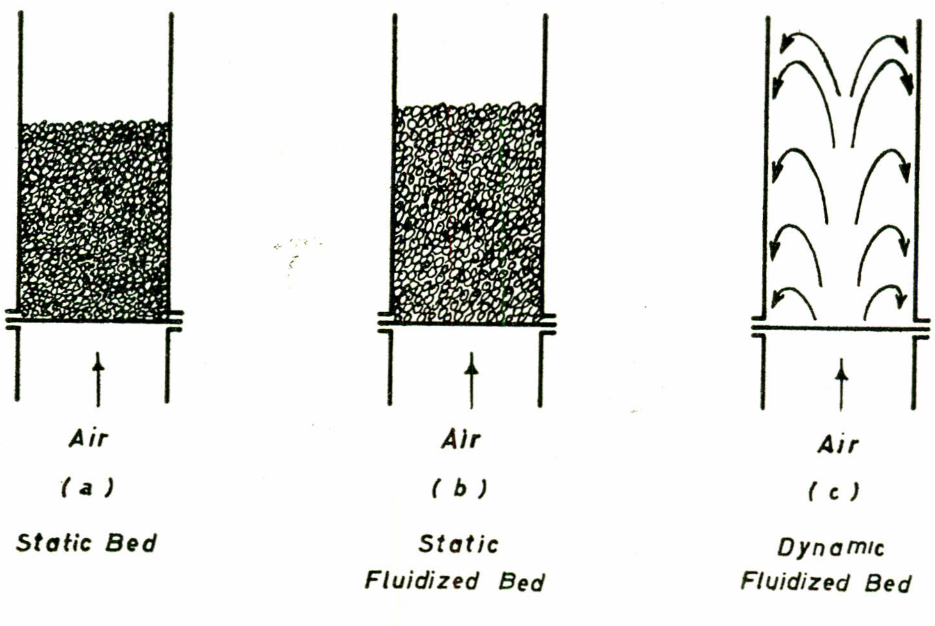

Fig. 1.

different sands varying in size from 0.01505 to 0.00202 inches (i.e. 36 to 300 mesh B.S.S.). The fluidizing agents used were air, carbon-dioxide and helium. The minimum fluid voidage has been related to the particle size and the particle shape.

Heerden, Nobel and Krevelen[2] studied the fluidization of vesicular materials namely silicon carbide, iron-oxide and coke with a number of fluidizing agents such as air, argon, carbon-dioxide, nitrogen and hydrogen mixtures, town gas and methane. They found that the critical mass velocity or critical mass gas-rates are proportional to the density of the fluidized beds at its maximum porosity and inversely proportional to the kinematic-viscosity of the fluidizing agent. This work does not cover the study of non-vesicular materials.

Later Leva, Shirai and Wen[3] studied the onset of fluidization for both the vesicular and non-vesicular solids, using liquids and gases over laminar and turbulent flows. The relationship given by these workers may be expressed as follows:

$$G_{mf} = C.dp^2.\ g_c.P_f(P_s\text{-}P_f)/\mu \text{ - - - - - } (1).$$

Where C is the function of dp. G_{mf}/μ. When $G_{mf} \leq 5$, equation (1) reduces to

$$G_{mf} = 68.76\ (dp.)^{1.8235}\ [P_f(P_s\text{-}P_f)^{0.8412}]/\mu^{0.822}$$

where G_{mf} is the minimum superficial mass velocity of the fluid in lb. mass/(hr.) (sq. ft.), dp is the diameter of the sphere having the same volume as the particle in inches, P_f and P_s are the densities of the fluid and solid, respectively in lbs.mass/ cubic ft., and μ is the fluid viscocity in centipoises. Though this equation covers a wider aspect of fluidization phenomena, it does not embody a wide range of particle size. Further it may also be seen that this equation is of general utility only when Re′ does not exceed 5. i.e. the equation is applicable to laminar-flow only. Stranco and Ermanno[4] have co-related V_{mf}, the minimum fluidization velocity, to the particle size dp, the true density of the solid P_s and the fluidizing agent P_f and the viscosity of the fluid μ_f by the equation:

$$V_{mf} = 2.92 \times 10^{-4}(dp)^{1.7}(P_s\text{-}P_f)g/\mu_f \text{ - - - } (2)$$

Again this study is limited to non-vesicular particles and does not cover a wide particle size range.

Apparatus and Experimental Procedure

The apparatus used is shown in Fig. 2. Compressed air from the compressor (A) is cooled to ambient temperature in a copper coil (B), immersed in water and led to the fluidization column (C) through a gasmeter (G). Valves, (V_1) and

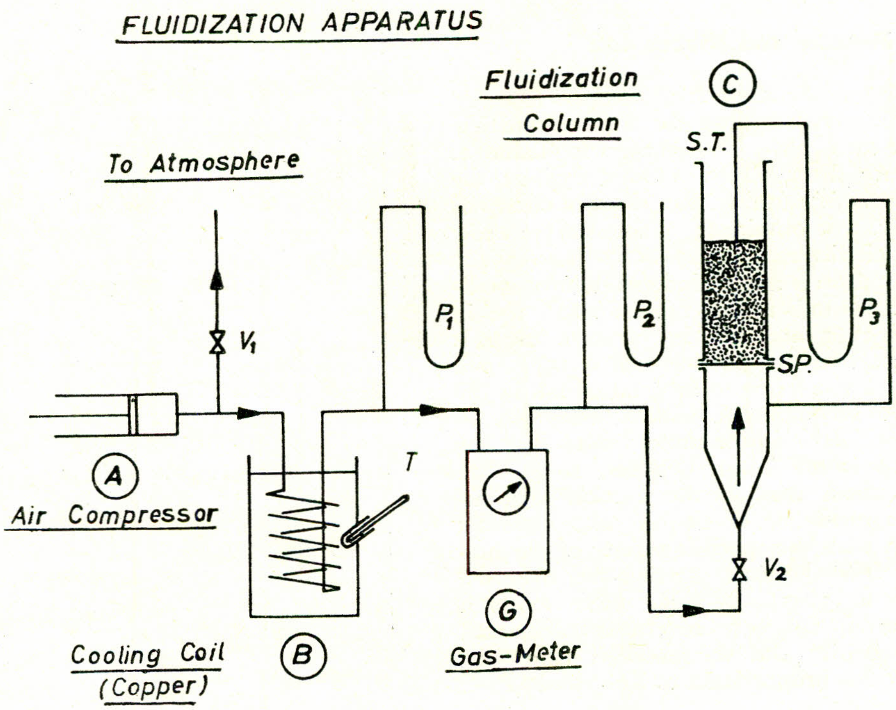

Fig. 2.

(V_2), are used to regulate the air supply to the fluidizing column which is a perspex cylinder of 2.5 inches internal diameter fitted onto a glass-funnel through a 300 mesh supporting screen (S.P.). A mercury manometer (P_1) to record the pressure after the cooling coil is provided. Another marcury manometer (P_2) is located near the fluidizing column to note the pressure of the inlet air whereas (P_3) is used to record with the help of the sliding-tube (S.T.) the pressure-drop across the granular bed.

As far as the experimental procedure is concerned 200 g. of the material of the known particle-size is fed into the fluidizing column. Compressor is then switched on and the air let into the column (C) by regulating valves (V_1) and (V_2), in volumes sufficient to bring about without particulate motion a maximum expansion of the bed. Air rates at pressure P_2 and the corresponding pressure drop across the bed are noted with the help of the sliding-tube (S.T.).

Materials

Since, in the present study it is desired to cover a broad spectrum of the particle-size, both the vesicular and non-vesicular materials namely coal, coke, bentonite, sand, limestone, felspar and iron-ore, are used (for densities see Table 1). The particle-sizes used are –10+12, –16+18, –30+36, –60+72, –85+100, –120+150, –150+170, and –170+200 mesh B.S.S.

Results and Discussion

Pressure Drop as the Function of Modified Reynolds' Number.—The pressure drop for a given particle size and air-rates have been shown in Table 1. When pressure drop, ΔP, is plotted against the modified Reynolds' number, Re′, a set of curves as shown in Fig. 3 is obtained. These curves show that for particle size range 0.271×10^{-3} to 0.754×10^{-3}, pressure drop is almost independent of modified Reynolds' number Re′, i.e. for small rise in the mass air-rate, the rise in pressure drop is optimum. Beyond the particle-size 0.754×10^{-3}, there is a slight rise followed by gradual fall in the pressure drop accompanied with a sharp rise in mass air-rates. It is interesting to note that the pressure drop is maximum between 10-20 Re′. This would mean that as the particle size diminishes, the resistance to air-flow also increases in proportion with the specific gravity of the materials used. For the same particle-size over the range 1.506 to 5.051×10^{-3} ft., there exists a linear relationship between the pressure drop and the particle density and the modified Reynolds' number i.e. ΔP is proportional to Re'^{-1} and $(P_t)^{-1}$

TABLE 1.—PRESSURE DROP AS FUNCTION OF MODIFIED RAYNOLDS NUMBER.

No.	Particle Size ft. × 10-3	Coal (1.390)* ΔP lbs/S. ft.	Coal Re′	Coke (1.510) ΔP	Coke Re′	Bentonite (2.370) ΔP	Bentonite Re′	Sand (2.610) ΔP	Sand Re′	Limestone (2.697) ΔP	Limestone Re′	Felspar (3.015) ΔP	Felspar Re′	Iron-ore (3.304) ΔP	Iron-ore Re′
1.	5.050	18.622	71.350	19.645	81.600	19.031	92.500	18.417	98.850	18.068	104.600	17.803	114.700	16.984	123.500
2.	3.037	19.235	25.380	19.844	30.390	19.645	34.290	18.826	34.710	18.622	38.200	18.622	44.200	18.068	50.950
3.	1.506	19.645	4.147	19.645	5.920	19.645	6.060	18.826	6.422	19.031	7.622	18.826	8.540	18.417	10.170
4.	0.754	18.826	0.545	19.235	0.751	19.235	0.896	17.598	0.826	18.212	0.805	17.803	1.046	17.598	1.102
5.	0.542	18.622	0.221	18.826	0.269	18.417	0.259	17.394	0.272	16.575	0.262	16.780	0.298	16.984	0.391
6.	0.375	18.068	0.088	17.189	0.080	16.780	0.092	16.371	0.097	15.757	0.104	16.166	0.102	16.371	0.119
7.	0.317	—	—	17.189	0.060	16.371	0.069	16.961	0.067	14.119	0.063	15.757	0.065	15.552	0.074
8.	0.271	17.598	0.037	—	—	—	—	15.552	0.046	15.961	0.039	14.938	0.043	15.347	0.052

*Bracketted figure indicates density.

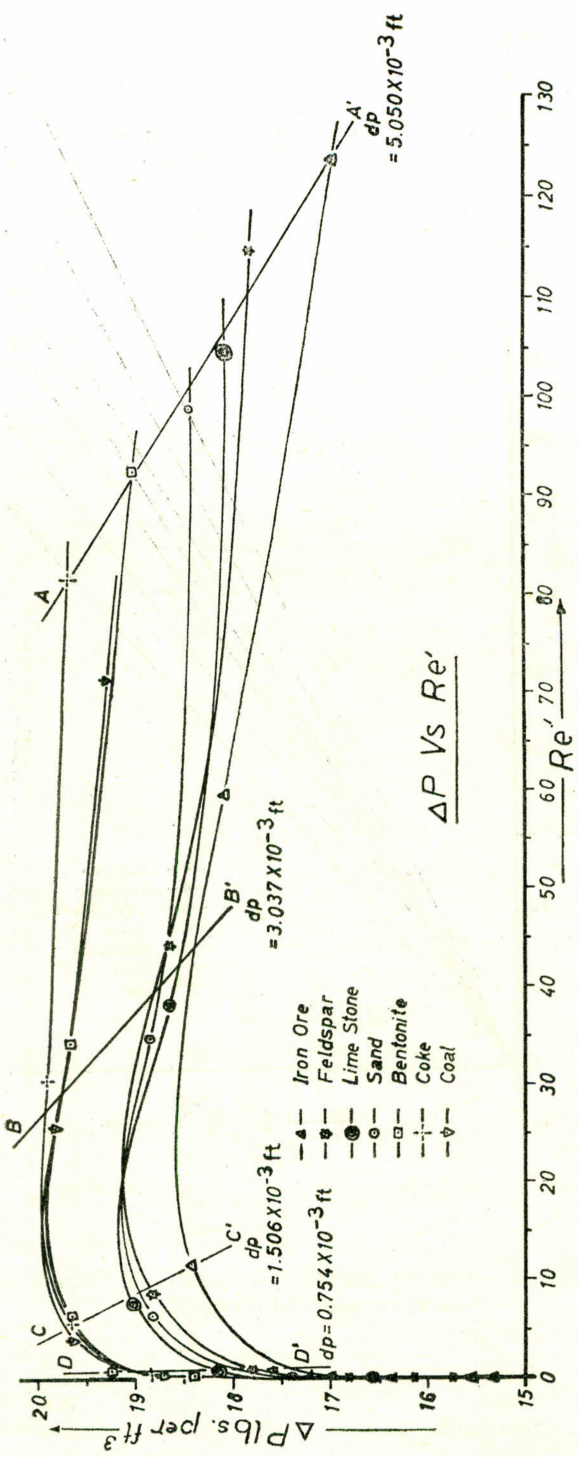

Fig. 3.

or as the pressure drop increases the modified Reynolds' number falls and so does the density. This fall becomes minimum between the particle size 0.754×10^{-3} and 1.506×10^{-3} ft. and thereafter the pressure drop becomes almost independent of the Re′. The behaviour of the materials, vesicular or non-vesicular, is almost alike but the coal differs at particle sizes 3.037×10^{-3} and 5.051×10^{-3} ft. Similar though not so pronounced, a discrepancy is also observed in the case of limestone but at a different particle size range, namely 1.506×10^{-3} and 3.037×10^{-3} ft.

Effect of the Particle Size.—The mass air-rates or the modified Reynolds' number Re′, is a smooth function of the particle size dp as shown in Fig. 4 where Re′ is plotted against dp. The set of curves indicates that Re′ rises with the increase in particle size and that they are in the order of the specific gravities of the materials used. Over the particle size range 0.271 to 5.050×10^{-3} ft., the value of Re′ for coal rises from 0.0366 to 71.35 and for iron-ore from 0.052 to 123.5. These curves also show that from the particle size 0.271 to 0.375×10^{-3} ft. the value of Re′ is very negligible, for dp 0.542 to 0.754×10^{-3} ft. Re′ is less than 2 and for dp 1.506 to 5.050×10^{-3} the value of Re′ rises from 2 to 120. This would suggest that for the small particle-size range minimum air-rates are required for the onset of fluidization.

When Re′ is plotted against dp^2 (Fig. 5) a set of straight lines of the same order as in Fig. 4 is obtained. These straight lines may be represented by the equation $Re' = K(dp)^2 - C$, where the values of K and C for different materials may be seen in Table 2. These results indicate that the value of K increases with the rise in the specific gravity of the materials.

Effect of the True Density.—On the basis of the data given in Table 1. when the modified Reynolds' number, Re′, is plotted against the true density P_t, Fig. 6, it will be noticed that for the smaller particle-sizes e.g. 0.754×10^{-3} and less, the relationship between Re′ and P_t is linear and that Re′ is almost independent of the true-density. This coincides with the previous conclusion under the study of pressure drop. For particle sizes 0.754×10^{-3} ft. and above, the rise in the value of the modified Reynolds' number is proportional to the specific gravity of the materials and as the overall particle size increases, the curves become steeper. Making use of a log-log plot, the relationship between modified Reynolds 'number and true density could be expressed by $\log(Re') = \log K (P_t)^n$ wherein the value of K changes from 18.25 to 0.33 and that of n changes from 0.395

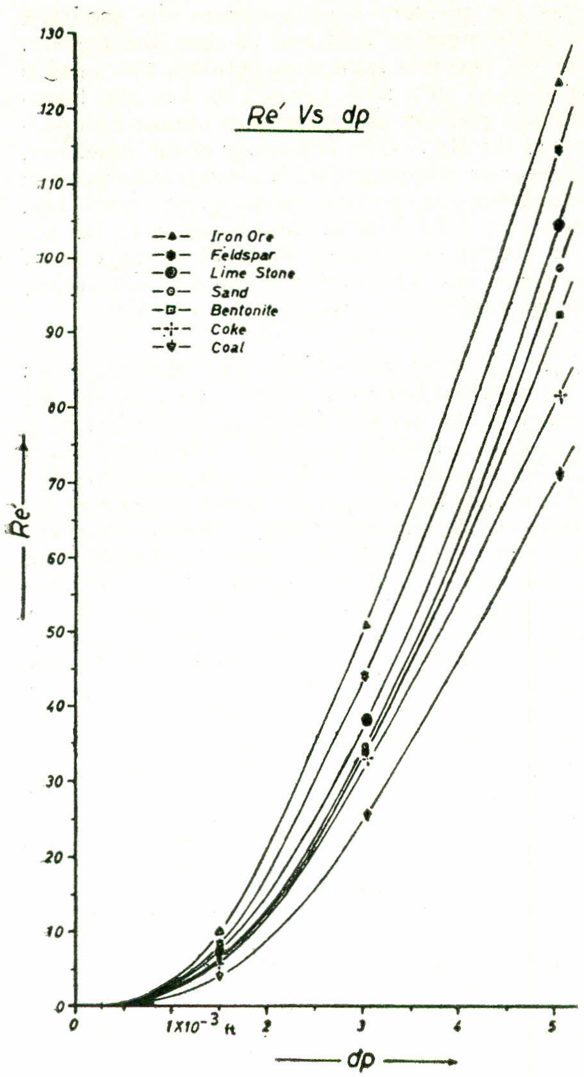

Fig. 4.

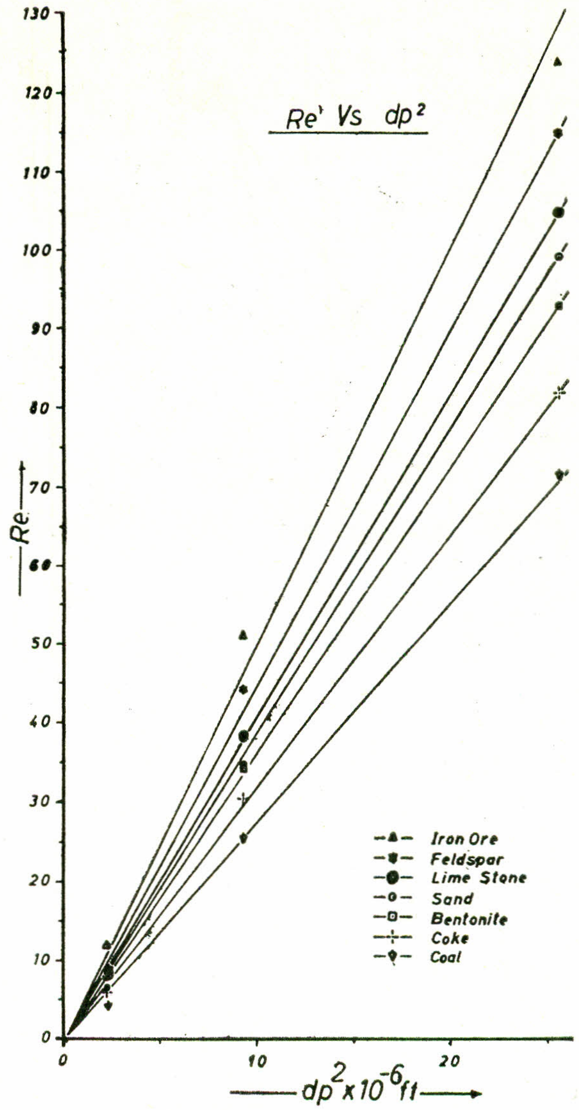

Fig. 5.

to 3.304 the Re′ rises from 0.030 to 1 for the particle-size 0.231 to 0.754×10^{-3} ft., 5 to 11.5 for the particle-size 1.506×10^{-3} ft., 27.5 to 50 for dp 3.037×10^{-3} ft. and 77.5 to 123 for the dp 5.051×10^{-3} ft. This would mean that the rise in the value of Re′ is not only the function of the particle size but also varies with the specific gravity of the material. This effect is less marked in smaller particle sizes but pronounced in higher sizes. No difference in behaviour is observed in vesicular (coke and iron-ore) and non vesicular

TABLE 2.—VALUES OF THE CONSTANTS K AND C FOR DIFFERENT MATERIALS.

No.	Material	K	C
1.	Coal	2.857	1.427
2.	Coke	3.240	0.920
3.	Bentonite	3.700	0.900
4.	Sand	3.900	0.100
5.	Lime-stone	4.117	0.198
6.	Felspar	4.615	0.765
7.	Iron-ore	5.000	—

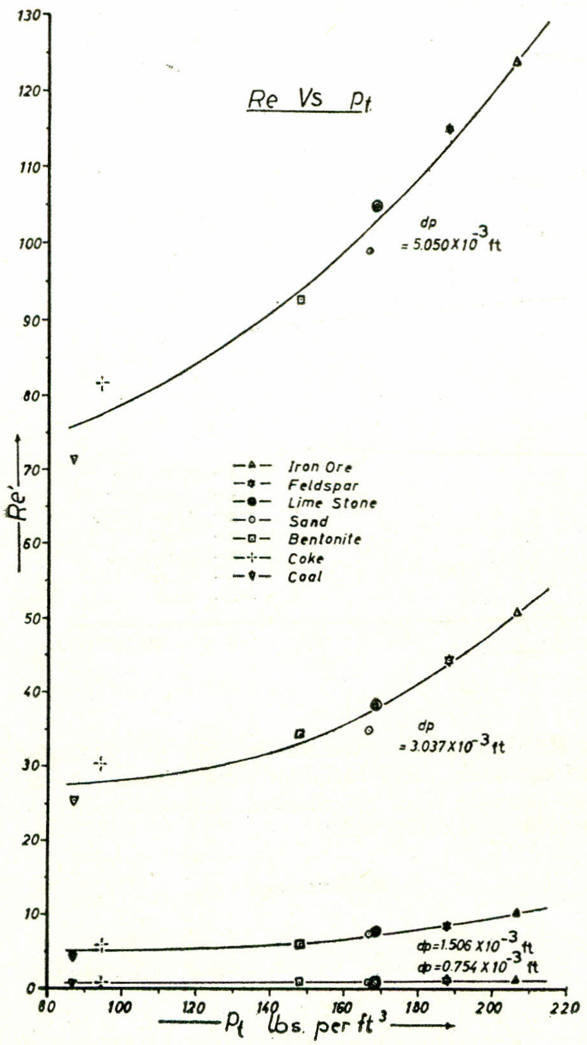

Fig. 6.

materials namely coal, bentonite, sand, limestone and felspar.

The Relationship between Re' and Voidage.—Under ordinary conditions where compressed air is passed through the bed., the space between the particles, i.e. the void, increases (Table 3). A departure from this rule has been noticed in case of coal, bentonite, sand, limestone, felspar and iron-ore, where a general trend (Fig. 7) is that the maximum voidage falls with the rise in the particle-size and thereafter either the fall continues or it rises (the fall in the voids is maximum for the particle-size range 0.271 to 0.754×10^{-3}). The behaviour of coke is most normal as indicated by its smooth

TABLE 3.— MODIFIED RAYNOLDS' NUMBER AS FUNCTION OF TRUE DENSITY, BULK DENSITY AND VOIDAGE.

No.	Particle Size ft. $\times 10^{-3}$	Materials: Coal		Coke		Bentonite		Sand		Limestone		Felspar		Iron-ore	
		Bulk density lbs./c.ft.	Voidage	Bulk density	Voidage	Bulk density	Voidage	Bulk density	Voidage	Bulk density	Voidage	Bulk density	Voidage	Bulk density	Voidage
1.	5.050	36.15	0.583	30.82	0.672	58.70	0.604	86.00	0.484	67.40	0.600	86.03	0.542	79.20	0.616
2.	3.037	35.50	0.592	33.95	0.640	56.70	0.617	87.55	0.475	68.35	0.594	83.20	0.557	81.80	0.604
3.	1.506	37.80	0.564	38.39	0.593	55.40	0.627	87.55	0.475	67.40	0.600	86.60	0.550	84.60	0.590
4.	0.754	38.10	0.561	43.40	0.540	52.50	0.645	87.55	0.475	65.60	0.610	86.03	0.542	89.10	0.568
5.	0.542	36.95	0.574	44.55	0.528	53.10	0.642	83.10	0.502	65.60	0.610	86.03	0.542	89.10	0.568
6.	0.375	34.90	0.598	45.37	0.519	50.40	0.660	76.80	0.540	64.80	0.615	81.80	0.564	89.10	0.568
7.	0.317	—	—	45.37	0.519	46.85	0.663	73.40	0.560	64.00	0.620	79.80	0.575	89.10	0.568
8.	0.271	34.19	0.606	—	—	—	—	72.30	0.566	63.20	0.625	80.45	0.571	86.00	0.583

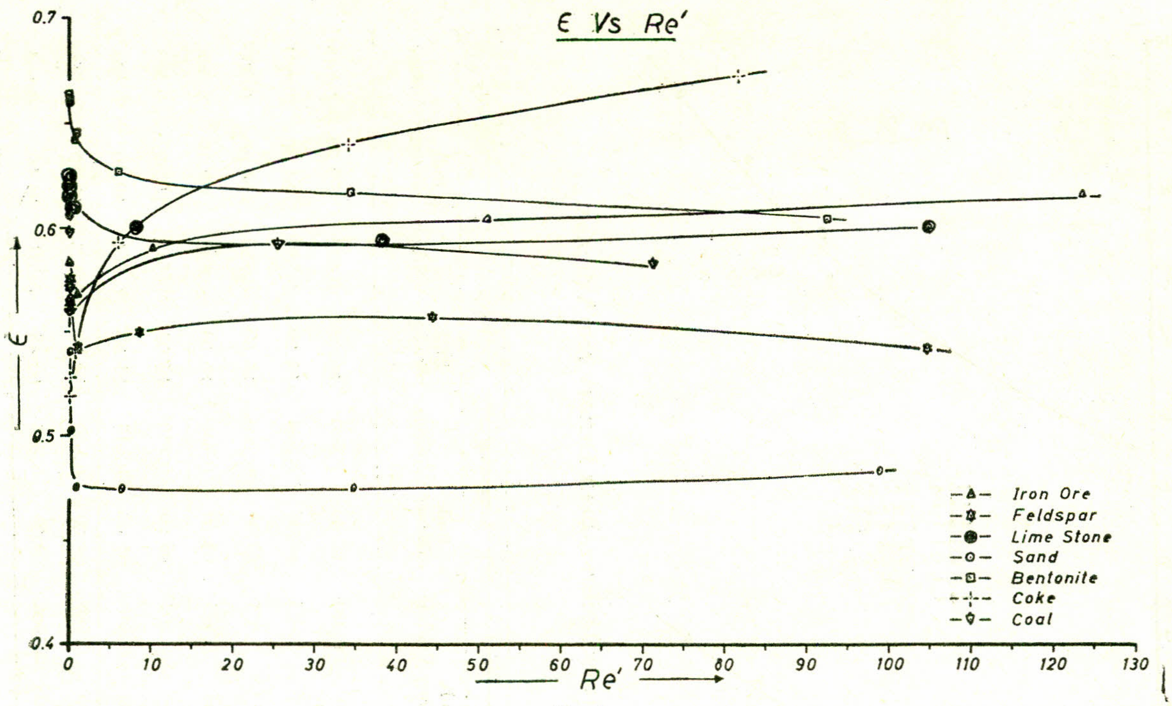

Fig. 7.

curve i.e. as the air-rates increase, the voidage also increase.

The divergence from the normal behaviour of all the materials (except coke) is not clearly understood. This might be due to the reason that ε Vs Re′ has been plotted for the different particle-size but when these variables were plotted for the *same* particle size, no marked difference in behaviour was observed.

NOTATIONS:

ε = Voidage of the 'static' fluidized bed. $(1 - \frac{P_B}{P_t})$; dp = Arithmatic-mean Sieve diameter of particle. Ft. ; ΔP = Pressure-drop across the granular bed. lbs./sq. ft.; Re′ = Modified Reynolds' number; P_t = True density of the solid. lbs./cu ft.; P_f = True density of the air lbs./c. ft.; P_B = Bulk-density lbs./c.ft.

References

1. M. Leva, M. Grummer, M. Weintraub and M. Pollchik, Chem. Eng. Progr., **44,** 619 (1948).
2. C.V. Heerden, A.P.P. Nobel and D.W.V. Krevelen, Chem. Eng. Sci. 1, 37-49(1951).
3. M. Leva, T. Shirai and C.Y. Wen. Genie Chim., **75,** 33 (1956).
4. Stranco Paolo and Ermanno Coppi, Chim. Ind. Milan, **43,** 1348 (1961).