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Gas Residence Time Distribution in Multistage Fluidised Beds*

H. BRAUER, M. SCHMIDT and Y. B. G. VARMA, Berlin

Abstract. The residence time distribution of the gas in multistage fluidised beds is studied, using Helium as tracer, for different conditions of the solids concentration, the number of stages and the height-to-diameter ratio of the stage. The results are compared with that of batch fluidisation with and without baffles and it is found that continuous fluidisation gives better flow characteristics of the gas and possesses a wider range of operation than batch fluidisation.

Zusammenfassung. Die Verweilzeitverteilung des Gases in mehrstufigen Wirbelschichtanlagen wurde untersucht. Als Spurengas diente Helium. Bei den Versuchen wurden die Partikelkonzentration, die Zahl der Wirbelschichtstufen und deren bezogene Höhe verändert. Ein Vergleich mit den Ergebnissen von Untersuchungen an absatzweise betriebenen Wirbelschichtanlagen ergaben, daß bei kontinuierlichem Durchfluß der fluiden und der partikelförmigen Phase durch die mehrstufige Anlage das Gas die engere Verweilzeitverteilung aufweist und daher zu günstigeren Betriebsbedingungen beiträgt.

Nomenclature

- C Tracer concentration in the effluent
- C_0 Tracer concentration at the inlet
- C_p Solids concentration (= 1-porosity)
- F Output tracer concentration for a unit step input of tracer
- θ Dimensionless time, time/total residence time

The experimental determination and an accurate analysis of residence time distribution is essential for the study of continuous flow systems. The significance is greater if the system possesses random movement of the components as is with gas fluidised beds. Kunii and Levenspiel [1] reviewed the experimental findings and gave a detailed discussion of the flow pattern of the gas as well as solids in fluidised beds. Nauman and Collinge [2] and Martyushin et al. [3] reported the contact-time distribution functions and their measurement in single-stage fluidised beds. The data, however, is scarce with respect to multistage fluidised beds and the only reference is that reported by Overcashier et al. [4] who observed increased spread in the gas residence times with increased solids concentration. This paper presents the experimental determination and the analysis of the flow pattern of the gas in multistage fluidised beds under different experimental conditions.

1. Experimental

The flow pattern of the gas is found out using hot-wire anemometer with Helium as tracer. Adler [5] reported the adaptability of anemometry for continuous measurement in unsteady concentration fields of binary gaseous mixtures. The experimental setup is shown in Fig. 1. The solids are continuously fed at the top of the column and air is introduced at the bottom through a distributor which ensures rotational symmetry in gas velocity distribution. Provision is made to introduce through the respective rotameters and a magnetic valve the tracer gas or alternatively an equivalent amount of air. The magnetic valve permitted an instantaneous change-over from air to Helium or vice versa. The experiments are conducted using step-input of the tracer gas and the results are found to agree well both when the tracer gas is introduced or switched-off from the system. Under steady conditions of operation, the tracer gas at a predetermined rate is instantaneously introduced and maintained at that initial concentration till the attainment of the constant level at the outlet, which is observed by continuously recording the anemometer reading. Similarly, under steady operation, the tracer gas is now switched-off and an equal amount of air is allowed into the system and the outlet reading is continuously recorded till the attainment of a constant value corresponding to the air.

Below is given the range of variables covered in the present study:

I. Type of fluidisation:
  1. Batch fluidisation without baffles
  2. Batch fluidisation with baffles
  3. Continuous fluidisation with restriction on solids flow, Viz. the bottom plate has perforations of smaller diameter than that corresponding to the rest of the sieve-plates.
  4. Continuous fluidisation with no restriction on solids flow, Viz. all the sieve-plates are identical

II. Number of stages: 1, 2, 5, 7 and 10

III. Height-to-diameter ratio of each stage: 1 and 2

IV. Type of solids: Glass beads of – 0.80, + 0.65 mm size

V. Type of baffles: Sieve-plates of 1 mm thick with 3.5 mm perforation diameter and 0.54 fractional free cross-sectional area. For case I.3, the bottom plate with 3.0 mm perforations is used.

* Dedicated to Professor Dr. Romano Gregorig on his 65th birthday.

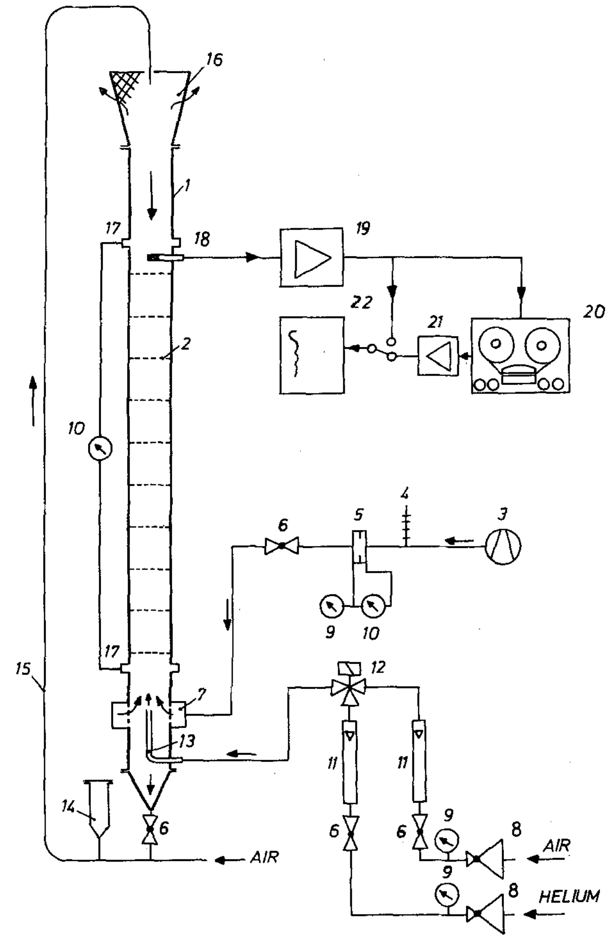

Fig. 1: Schematic diagram of the experimental setup.
1. Perspex column, 62 mm, 2. Sieve plate, 1 mm thick, 3.5 mm hole dia., 0.54 free cross-sectional area, 3. Air compressor, 4. Thermometer, 5. Orifice meter, 6. Control valve, 7. Air distributor, 8. Pressure reducer, 9. Pressure gauge, 10. Differential pressure gauge, 11. Rotameter, 12. Magnetic 3-way valve, 13. Tracer inlet, 14. Solid input, 15. Solids recycle, 16. Top of the column (air outlet), 17. Pressure tappings, 18. Hot-wire anemometer sensor, 19. Anemometer amplifier, 20. Philips technical 7-track tape recorder. Recording: 30 in./Sec., Replay: 3.75 in./Sec., 21. Active low pass filter, 22. High speed x-t recorder. Recording: 120 and 600 mm/min. Full scale: 0.5 Volts

VI. Solids concentration: 0.03 to 0.282
VII. Particle Reynolds number: 6500 to 27000

2. Results and discussion

Fig. 2 presents the calibration curve, whereby it can be seen that the Helium concentration on the abscissa is linearly related to the anemometer reading when the former lies below 1%, which is the range of operation in the present study.

The change in the flow characteristics of the gas due to sieve-plates is shown in Fig. 3 for the empty column and in Fig. 4 for batch fluidisation, whereby it can be seen that baffles reduce the spread of gas residence times in both the cases. The provision of baffles in batch fluidised bed reduces the solids concentration gradient from the bottom to the top of the column and limits the random movement of the solids in the axial direction, which, in turn, reduces the longitudinal mixing of the gas. Further, it is found that the overall solids concentration influences the effect of baffles on the flow characteristics of the gas. Thus, with increase in solids concentration, the difference in the flow pattern of the gas in the baffled and unbaffled systems increases, the latter exhibiting large fractions of the fluid overstaying in the system. The range of stable operation is limited with the unbaffled system, as solids concentrations greater than 0.1 led to bubble formation, a phenomenon which occurred in the baffled system for $C_p > 0.2$.

Fig. 5 shows the dependency of the gas residence time distribution on solids concentration in batch fluidised bed with baffles. It can be seen from the figure that, at low solids concentration, say $C_p < 0.1$, the influence of solids concentration on the flow behaviour of the gas is significant resulting in the spread of residence times with increased solids concentration. This phenomenon may be attributed to the increased gas mixing caused by the large solids concentration. A slow-moving fluid layer exists near the wall in an empty tube, irrespective of the type of flow, because of the no-slip condition at the wall. The fluid elements in this layer remain in the system for a considerably longer time than that corresponding to the bulk of the fluid. If solids are now introduced into the system, the randomly moving solid particles have a tendency to continuously stir and thereby replace the slow moving fluid layer at the wall, thus enabling favourable mixing conditions. On the other hand, the moving solid particle brings a wake of fluid at its back and has a fluid film around its surface, the cumulative effect being to lead to mixing of fluid elements of different ages. Thus, at low solids concentration, say $C_p < 0.05$, the flow characteristics of the gas improves over that corresponding to the empty

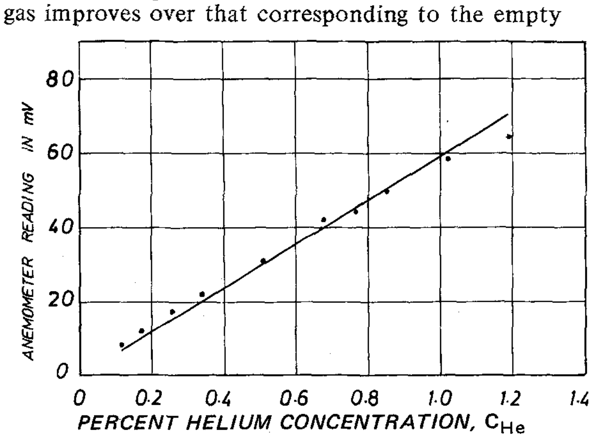

Fig. 2: Calibration curve

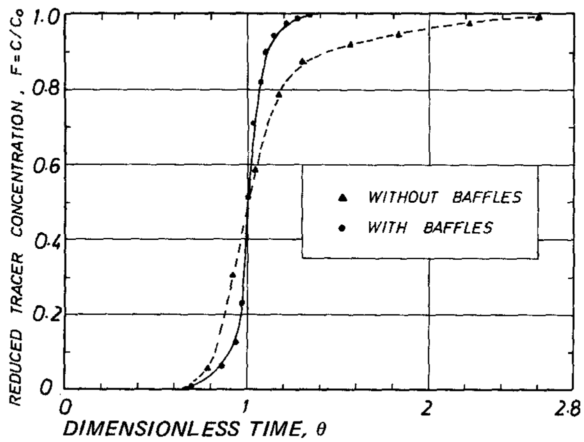

Fig. 3: Flow pattern of gas in the empty column

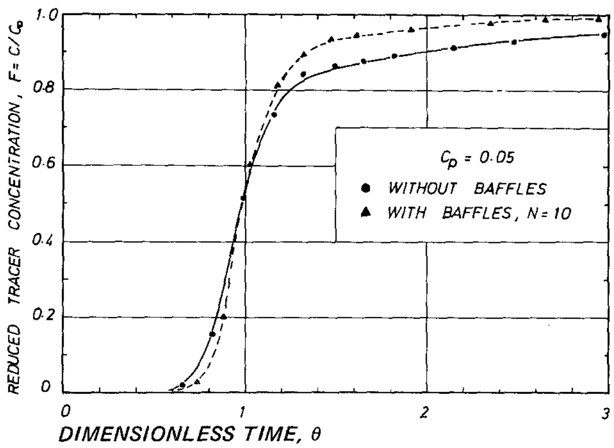

Fig. 4: Effect of baffles on the flow pattern of gas in batch fluidised beds

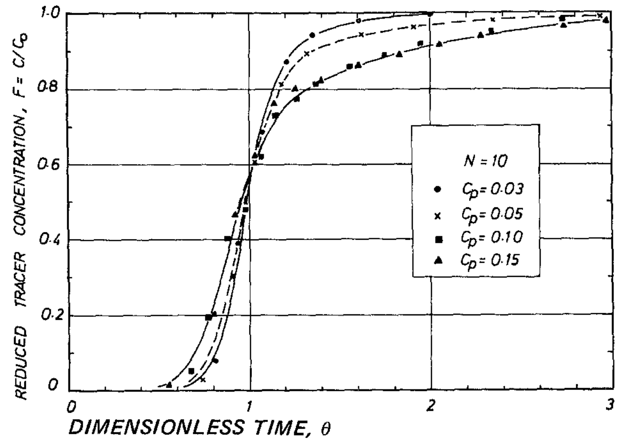

Fig. 5: Effect of solids concentration on the flow pattern of gas in batch fluidised bed with baffles

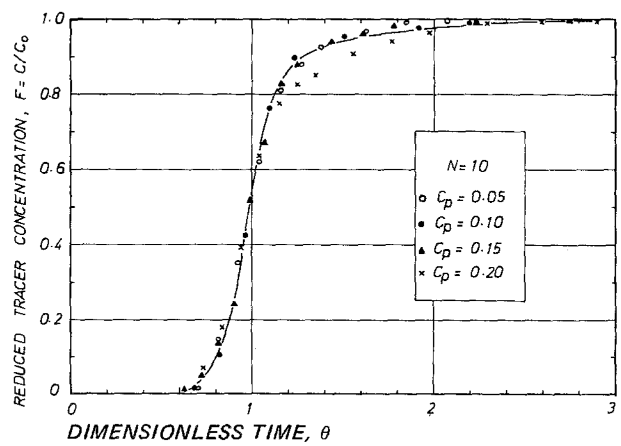

Fig. 6: Effect of solids concentration on the flow pattern of gas in continuous fluidised bed with restriction on solids flow rate

column with baffles. An increase in solids concentration leads to increased axial mixing of the gas with wide distribution of the gas residence times. However, at high solids concentrations, say $C_p > 0.1$, the movement of the solid particles is restricted and hence no appreciable change in the flow characteristics of the gas occurs with increased solids concentration. With solids concentrations greater than 0.2, the free cross-sectional area available for the flow of the gas reduces considerably leading to the formation of bubbles which move discontinuously through the bed. The observations in general are applicable even for batch fluidisation without baffles, except that the range of operation below the bubble formation steadily decreases with increase in height-to-diameter ratio of the stage.

Results on continuous fluidisation in the multistage column with the bottom plate of 3.0 mm perforations, the rest being of 3.5 mm, showed little change in the flow behaviour of the gas with the solids concentration, Fig. 6, when $C_p \leqslant 0.15$, above which increased spread in gas residence times is noticed with increase in solids concentration. Similarly, for $C_p \leqslant 0.15$, continuous fluidisation with identical sieve-plates showed negligible effect of solids concentration on gas residence time distribution (Fig. 7). However, a comparison of the results of continuous fluidisation with that of batch fluidisation with baffles shows that the former gives better flow characteristics of the gas with less of fluid overstaying or understaying in the system (Fig. 8). This difference in the gas residence time distribution between the two types of operation is found to be large when $C_p > 0.1$. The difference in the behaviour of the system between continuous fluidisation and batch fluidisation with baffles can be visualised by noting the unidirectional movement of the solids in the former in contrast to the random movement in the latter. The solids are continuously fed at the top and removed at the bottom of the column and hence there is no possibity for the existence of solids concentration gradient in continuous fluidisation. Moreover, in continuous fluidisation, the solids move from stage to stage preferably near the wall and thus replace the slow moving fluid layer at the wall, whereas the solids do not easily interchange between stages in batch

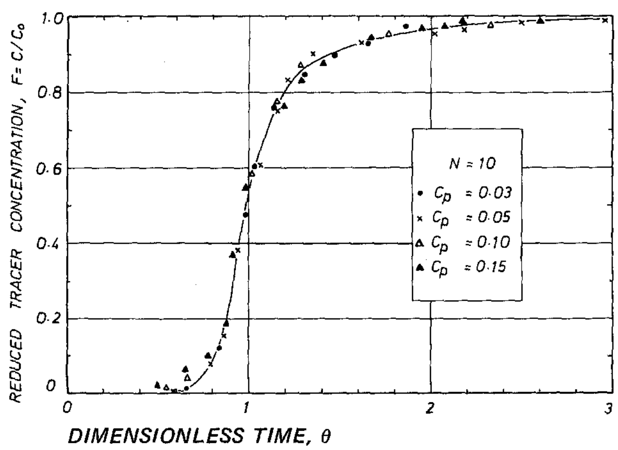

Fig. 7: Effect of solids concentration on the flow pattern of gas in continuous fluidised bed with no restriction on solids flow rate

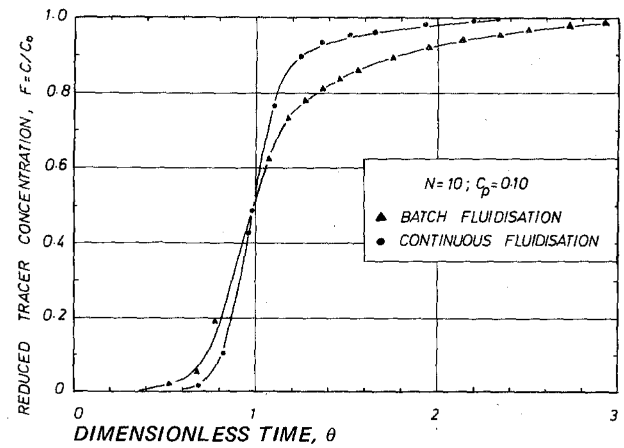

Fig. 8: Comparison of the flow pattern of gas in batch fluidised bed with baffles and continuous fluidised bed with restriction on solids flow rate

fluidisation which makes it possible for slow moving regions to exist near the tube wall. This aids the formation of dead pockets of gas leading to mixing of fluid elements of different ages.

In conclusion, the experimental results indicate the marked influence of the type of fluidisation on the flow characteristics of the gas through the fluidised bed. The flow behaviour of the gas is closely related to the mixing of solids and the overall solids concentration in the gas fluidised beds. Thus, provision of baffles in the batch fluidised bed reduces the solids concentration gradient along the length of the column, restricts the axial mixing of the solids and thus decreases the longitudinal mixing of the fluid. Further, the positive influence of the sieve-plates in breaking the large gas bubbles moving through the bed, extends the range of operation below bubble formation, when baffles are used, to the solids concentration of 0.2 compared to 0.1 in batch fluidisation without baffles. The bubble formation leads to non-uniform contact between the solids and the gas and hence needs elimination when dealing with chemical reactions as for example the hetrogenous catalytic reactions. Continuous fluidisation has not only an identical range of operation as that of batch fluidisation with baffles, but gives better flow pattern of the gas with less of fluid understaying or overstaying in the system, a criteria which is of particular significance in fast multiple reactions. Further, the solids concentration has negligible effect in continuous fluidisation on the residence time distribution of the gas. This permits the operation of the fluidised bed at different solids concentration without markedly affecting the flow behaviour of the gas. In cases where the solids are to be regenerated as for example in some hetrogenous catalytic reactions, the facility of the recycle of solids in continuous fluidisation has decided advantages over batch fluidisation with baffles. The use of the bottom plate of smaller perforations than that corresponding to the rest of the plates in the column is found to have little effect on the flow behaviour of the gas in the present range of experimental study. On the other hand, the bottom plate with smaller perforations permits the control of the residence time of the solids which is of significance in transfer operations. It is found that the number of stages has little effect on the residence time distribution of the gas. However, when the number of stages is as low as 2, the flow characteristics of the gas exhibited large fractions of fluid understaying or overstaying in the system.

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o. Professor Dr.-Ing. H. Brauer,
Dipl.-Ing. M. Schmidt,
Institut für Verfahrenstechnik der Technischen Universität Berlin

Dr. Y. B. G. Varma, Assistenz-Professor am Indian Institute of Technology Madras,
z. Z. als Stipendiat der Alexander-von-Humboldt-Stiftung im Institut für Verfahrenstechnik der Technischen Universität Berlin

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