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Study and modelling of mass transfer in magnetically stabilized fluidized beds†

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Abstract—The mass transfer in magnetically stabilized and semi-stabilized beds has been studied experimentally using the drying of moist air in beds of alumina–steel mixtures. Two parameters, bed efficiency and efficiency factor have been used to compare the behaviour of the different beds. The accuracy of the theoretical models developed has been tested using the results obtained. The models corresponding to the classical fluidized bed do not agree with experimental data; however, when these models are modified to take into account the effect of magnetic stabilization, the accuracy is much better.

INTRODUCTION

ALTHOUGH in recent years an important effort has been devoted to improving the knowledge of the behaviour of magnetically stabilized fluidized beds (MSFB), very few papers have dealt with the study of mass transfer in them.

The influence of a magnetic field on conversion in ammonia synthesis was studied by Ivanov and Zrunchev [1] and Zrunchev and Popova [2], and Zrunchev [3] studied the nitrogen/hydrogen mixtures purification, as well as the influence of hydrodynamics on conversion [4]. Recently, these beds have been used for drying air and studying the influence of different variables on the performance of the operation [5–7].

In this work, data obtained in the dehumidification of moist air are used to compare the gas/solid contact in MSFB with respect to that corresponding to fixed and fluidized beds. The influence of the different degrees of bubbling is studied, and a mathematical model is developed.

EXPERIMENTAL SETUP

The experimental setup consisted of a fluidization column (Fig. 1) made of poly (methyl methacrylate), 51 mm i.d., installed inside a coaxial electrical coil, 120 mm in diameter.

Air, previously filtered, was humidified to saturation, and mixed with fresh air to control its final condition; this air, at 30°C and relative humidity 90%, entered the column. The humidity of the air—upstream and downstream in the bed—was determined by gas chromatography; its temperature, measured at bed inlet and outlet, was always almost constant, with a maximum variation of 2°C.

The bed consisted of a mixture (50% in mass) of steel and alumina particles (see Table 1 for particle properties). The total mass of particles in the bed was always 700 g, and always with $L/D > 2$. The bed column was not thermally isolated, thus balancing the heat generation due to adsorption.

Fixed bed data were obtained in the same setup but with reverse flow.

RESULTS AND DISCUSSION

To represent the behaviour and performance of the bed, the following parameters were defined:

bed efficiency

$$\eta = \frac{C_i - C_e}{C_i}; \tag{1}$$

efficiency factor with respect to fluidized bed

$$E_M = 1 - \eta_F/\eta_s; \tag{2}$$

efficiency factor with respect to fixed bed

$$E'_M = 1 - \eta_f/\eta_s. \tag{3}$$

The 'efficiency factor' allows comparison between the MSFB and the fluidized and fixed beds, as well as between the different hydrodynamical regimes at which the MSFB can be operated. η and E_M values always range from 0 to 1, and the E'_M value can vary from -1 to 1.

The variation of E_M as a function of magnetic field intensity has been plotted in Fig. 2, at different operating times, for a completely stabilized bed ($u < u_b$). It can be observed that in all cases $E_M > 0$; this indicates that the performance of the bed is higher than that corresponding to a classical bubbling fluidized bed. This can be attributed to the lack of bubbles, and therefore to the elimination of the by-pass of gas inherent in bubbling beds. It can be observed also that the efficiency factor increases with H indicating that the gas/solid contact increases with the magnetic field

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NOMENCLATURE

C	concentration of water in the air [kg kg^{-1}]
C_E	value of C in the emulsion phase [kg kg^{-1}]
$\bar{C}_E^*$	value of C in the gas in equilibrium with a concentration C_s in the solid [kg kg^{-1}]
C_e	value of C at bed outlet [kg kg^{-1}]
C_i	value of C at bed inlet [kg kg^{-1}]
C_s	concentration of water in the solid [kg kg^{-1}]
C_s^*	concentration of water in the solid surface [kg kg^{-1}]
$\bar{C}_s$	average value of C_s in all the solid in the bed [kg kg^{-1}]
d	particle diameter [μm]
E_M	efficiency factor with respect to a classical fluidized bed
E'_M	efficiency factor with respect to a fixed bed
H	magnetic field intensity [A m^{-1}]
K_a	adsorption velocity constant [s^{-1}]
k	number of transfer units between the emulsion gas and the solids
L	bed height [m]
M_a	mass of fresh adsorbent [kg]
m	slope of adsorption isotherm
S	cross-sectional area of the bed [m^2]
t	time [s]
u	superficial gas velocity [m s^{-1}]
u_b	transition velocity [m s^{-1}]
u_{mf}	minimum fluidization velocity [m s^{-1}]
z	vertical distance to the distributor [m].

Greek symbols

η	bed efficiency
η_F	fluidized bed efficiency
η_f	fixed bed efficiency
η_s	MSFB efficiency
ρ_p	particle density [kg m^{-3}].

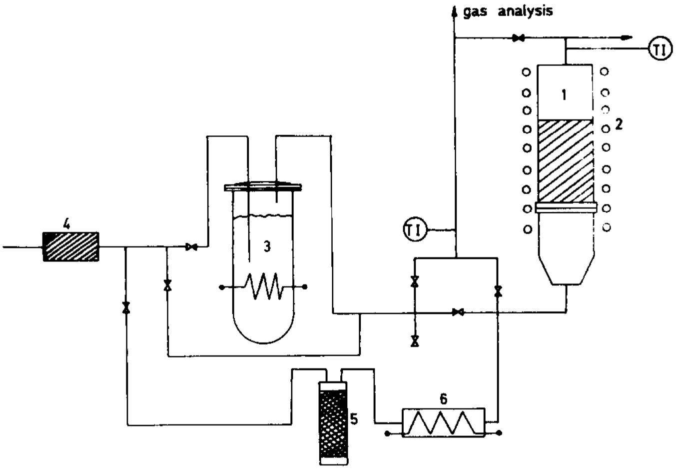

FIG. 1. Experimental setup: (1) fluidized bed column; (2) magnetic coil; (3) humidifier; (4) filter; (5) drying; (6) heating.

intensity. This better contact is attributed to the arrangement of particles following the field lines [4, 8, 9] which brings about an increase in bed voidage, diminishing the coordination number—contact points between particles—and thus increasing the contact between the solid and the gas [4–7].

Figure 3 shows the same plot, but covering a range of H and u/u_b values which corresponds to both a stabilized bed ($H > 3000$ A m^{-1}) and a semi-stabilized bed ($H < 3000$ A m^{-1}). It can be observed that even

Table 1. Characteristics of the particles

Material	d (μm)	ρ_p(kg m^{-3})	shape factor
Steel	350–420	7500	0.9
Alumina	630–890	2080	0.7

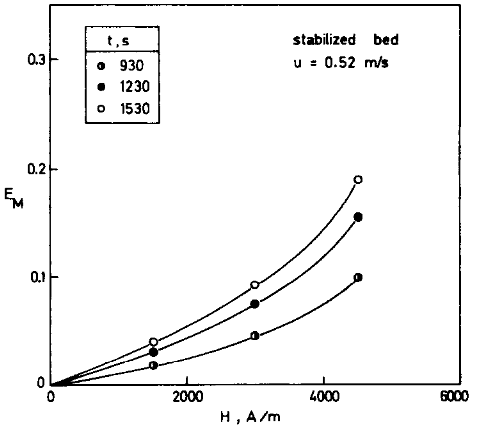

FIG. 2. Variation of E_M as a function of magnetic field intensity for a stabilized bed.

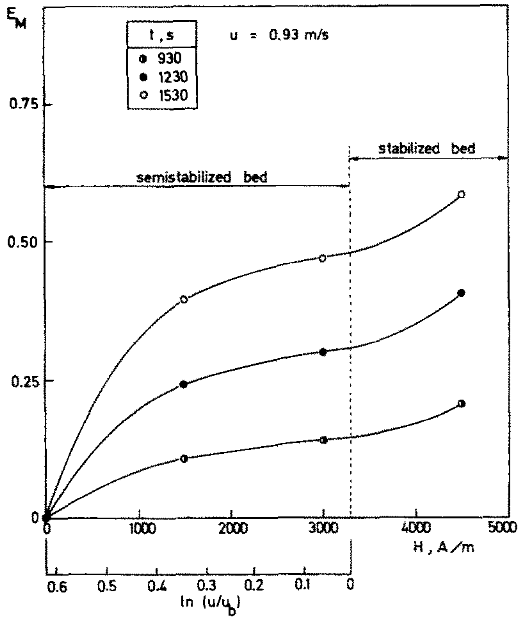

FIG. 3. Variation of E_M as a function of magnetic field intensity in semi-stabilized and stabilized conditions.

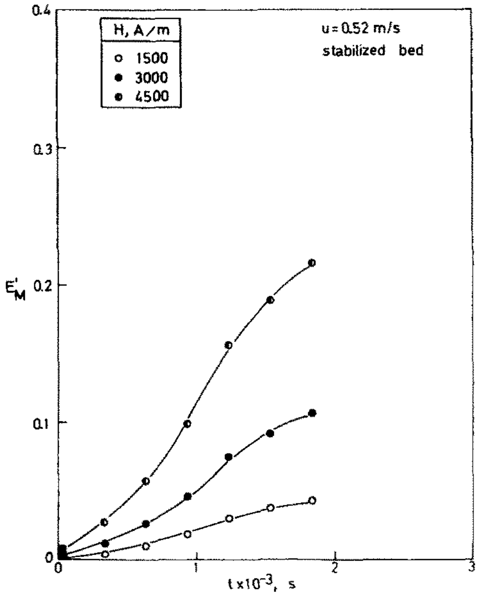

FIG. 4. Variation of E'_M as a function of time for stabilized bed conditions.

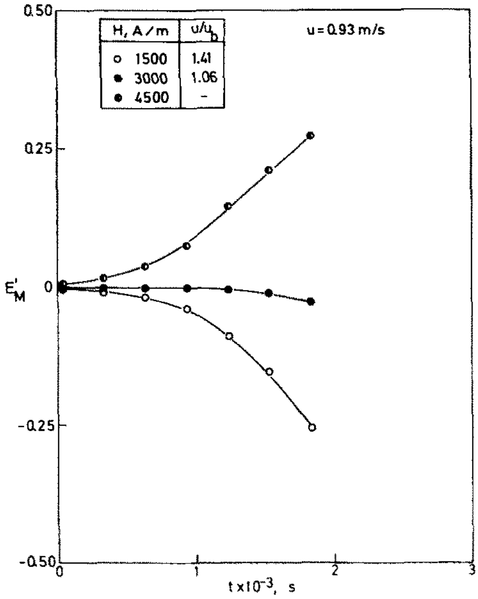

FIG. 5. Variation of E'_M as a function of time for a stabilized bed (4500 A m^{-1}) and two semi-stabilized beds (1500 and 3000 A m^{-1}).

in the semi-stabilized state the performance is better than that corresponding to a fluidized bed, as the degree of bubbling is smaller and thus the by-pass of gas is lower. As the magnetic field intensity increases the efficiency factor increases as well, and when the bed becomes fully stabilized the trend of the curves is the same as that in Fig. 2.

The comparison between a stabilized and a fixed bed can be seen in Fig. 4, where the efficiency factor E'_M has been plotted as a function of time for three different values of magnetic field intensity. Again the performance is better in the stabilized bed, E'_M being always greater than 0. This can be attributed to a certain degree of movement in the MSFB, which allows a better use of the whole surface of particles, increasing what could be called the 'effective specific surface' of the bed. It can be observed also how the gas/solid contact improves again with the magnetic field intensity, due to the bed expansion and the consequent increase in the exposure of particles surface to gas flow.

Finally, Fig. 5 shows the comparison between the fixed bed behaviour and the stabilized and two semi-stabilized beds. The value of E'_M is always less than 0 for the semi-stabilized bed, showing the negative effect of bubbling (as $u > u_b$, a certain degree of bubbling exists) on the gas/solid contact and, therefore, on the performance from the point of view of mass transfer.

MODELLING

The existing models for mass transfer in fluidized beds can be modified to reproduce the behaviour of an MSFB. The present modelling has been based on the two-phase theory. In the case of a semi-stabilized bed, bubbling has been supposed to appear at $u = u_b$; in the case of a stabilized bed, of course, bubbles are not taken into account.

The operation has been supposed to be isothermal, as the difference between inlet and outlet gas temperatures was always less than 6.7%. The diameter of bubbles has been calculated with the Mori and Wen correlation [10], with a wake volume fraction equal to 0.25 [11]; the velocity of bubbles has been calculated with the Davidson and Harrison equation [12], their initial diameter with the Geldart correlation [13], and their volume with the Partridge and Rowe equation [14]. The net flow exchanged between the two phases

Table 2. Standard deviation of the different models

Model	Stabilized bed (%)	Semi-stabilized bed (%)
Classical fluidization. Perfect mixing	30	29.3
Classical fluidization. Plug flow	37	38.6
Stabilized bed. Perfect mixing	11.9	—
Stabilized bed. Plug flow	4.4	—
Semi-stabilized bed. Perfect mixing	—	8.5
Semi-stabilized bed. Plug flow	—	12.8

has been defined by the Davidson and Harrison equation [15]. The simplifying assumption (already used by Hymore and Laguerie [16]) of a linear adsorption isotherm in the range (C_s^*; $\bar{C}_s$) has been made. To obtain the solutions for a classical fluidized bed, these equations have been solved following the procedure proposed by Orcutt *et al.* [17].

In the case of a stabilized bed, we can write

$$u(C_i - \bar{C}_E^*) = \frac{M_a K_a m}{S}(C_E - \bar{C}_E^*) \tag{4}$$

and solving it for the humidity of outlet gas

$$C_e = \bar{C}_E^* + (C_i - \bar{C}_E^*)/k. \tag{5}$$

In the case of plug flow

$$u\frac{\mathrm{d}C_E}{\mathrm{d}z} = -\frac{M_a K_a m}{SL}(C_E - \bar{C}_E^*). \tag{6}$$

With the boundary condition $z = 0 \Rightarrow C_E = C_i$, the solution of equation (6) gives

$$C_e = \bar{C}_E^* + (C_i - \bar{C}_E^*)\exp(-k). \tag{7}$$

In both cases, k has been defined as in ref. [16].

For a semi-stabilized bed, the correlations for the calculation of bubble characteristics are modified by substituting u_{mf} by u_b; the mass balances are those used by Hymore and Laguerie [16], but modified according to $u_{mf} = u_b$. The solutions to these equations are those proposed by Orcutt *et al.* [17], with the appropriate modifications.

The values predicted by using these models have been compared with the experimental data for $t = 30$ s, in order to guarantee the same condition of adsorbent in all cases with a practically constant driving force (at higher values of t the situation would be quite different, as the unit was operated in batch regime). The standard deviation of the different models with respect to the experimental data can be seen in Table 2.

The comparison between the models corresponding to the classical fluidized bed and the experimental results obtained with the MSFB shows that the agreement is very bad. However, it is much better when those results are compared with the corrected models developed for the MSFB, the plug flow model being better; this is in good agreement with the behaviour that could be expected from the arrangement of particles following field lines, which is the basis of some MSFB hydrodynamical models [4, 8, 9]. In the case of a semi-stabilized bed, it can be seen that the classical fluidized bed models predict values quite different from the experimental ones. Nevertheless, the agreement of values predicted from the modified models is fairly good, with approximately the same accuracy for both (perfect mixing and plug flow) models.

CONCLUSIONS

The mass transfer efficiency of the MSFB is always better than that corresponding to the classical fluidized bed. When compared with a fixed bed, the efficiency is better at $u < u_b$ and worse at $u > u_b$. This is due to the effect of the magnetic field on bubbling. The efficiency factors, E_M and E'_M, increase with the magnetic field intensity. This is attributed to the increase in bed voidage and to the arrangement of particles following the magnetic field lines, these effects improving the contact of particles with the gas.

The two-phase models—with plug flow or perfect mixing in the emulsion phase—corresponding to the classical fluidized bed do not agree with experimental data. Nevertheless, when these models are modified by introducing the effect of magnetic stabilization, the agreement is satisfactory for both stabilized and semi-stabilized beds.

REFERENCES

1. D. G. Ivanov and I. A. Zrunchev, A new method of ammonia synthesis at high pressures involving fluidization of the catalyst in a magnetic field, *C. r. Acad. bulg. Sci.* **22**(12), 1405 (1969).
2. I. Zrunchev and T. Popova, The effect of the field on TBE magnetically structured catalyst layer in ammonia synthesis under pressure, *Commun. Dep. Chem.* **12**(1/2), 206 (1983).
3. I. A. Zrunchev, Method for purification of nitro-hydrogen mixture from carbonic oxide, *C. r. Acad. bulg. Sci.* **27**(9), 1215 (1974).
4. I. A. Zrunchev, A magnetically stabilized fluidized catalyst bed model, *Commun. Dep. Chem.* **16**(3), 285 (1983).
5. J. Arnaldos, Estudi de l'estabilització dels llits fluiditzats sòlid-gas mitjançant l'aplicació d'un camp magnètic, Doctoral Thesis, Universitat Politècnica de Catalunya, Barcelona (1986).
6. J. Arnaldos, J. Casal and L. Puigjaner, Heat and mass transfer in magnetically stabilized fluidized beds. In *Fluidization V* (Edited by K. Ostergaard and A. Sorensen), p. 425. Engineering Foundation, New York (1986).
7. J. Arnaldos, J. Casal and L. Puigjaner, Transferencia de materia en lecho fluidizado estabilizado, *Proc. of the IV Jornadas de Fluidización*, p. 3-1. Madrid (1986).
8. A. Lucas, J. Casal and L. Puigjaner, Fluidized bed stabilization with a magnetic field: transition conditions and mixed systems. In *Fluidization IV* (Edited by D. Kunii and R. Toei), p. 129. Engineering Foundation, New York (1984).
9. J. Arnaldos, J. Casal, A. Lucas and L. Puigjaner, Magnetically stabilized fluidization: modelling and application to mixtures, *Powder Technol.* **44**, 57 (1985).

10. S. Mori and C. Y. Wen, Estimation of bubble diameter in gaseous fluidized beds, *A.I.Ch.E. Jl* **21,** 109 (1975).
11. D. Kunii and O. Levenspiel, Bubbling bed model. Model for the flow of gas through a fluidized bed, *Ind. Engng Chem. Fundam.* **7,** 446 (1968).
12. J. F. Davidson and D. Harrison, Behaviour of a continuously bubbling fluidized bed, *Chem. Engng Sci.* **21,** 731 (1966).
13. D. Geldart, The effect of particle size and size distribution on the behaviour of gas-fluidised beds, *Powder Technol.* **6,** 201 (1972).
14. B. A. Partridge and P. N. Rowe, Analysis of gas flow in a bubbling fluidized bed when cloud formation occurs, *Trans. Instn Chem. Engrs* **44,** 349 (1966).
15. J. F. Davidson and D. Harrison, *Fluidization.* Academic Press, London (1971).
16. K. Hymore and C. Laguerie, Analysis and modelling of the operation of a counterflow multistage fluidized bed adsorber for drying moist air, *Chem. Engng Process.* **18,** 255 (1984).
17. J. C. Orcutt, J. F. Davidson and R. L. Pigford, Reaction time distributions in fluidized catalytic reactors, *Chem. Engng Prog. Symp. Ser.* **58,** 1 (1962).

ETUDE ET MODELISATION DU TRANSFERT DE MASSE DANS DES LITS FLUIDISES MAGNETIQUEMENT STABILISES

Résumé—Le transfert de masse dans des lits magnétiquement stabilisés et semi-stabilisés, a été étudié expérimentalement en utilisant le séchage d'air humide dans des lits de mélanges alumine–acier. Deux paramètres, efficacité du lit et facteur d'efficacité, ont été utilisés pour comparer le comportement de différents lits. La précision des modèles théoriques développés est testée. Les modèles correspondant au lit fluidisé classique ne s'accordent pas avec les données expérimentales ; néanmoins quand ces modèles sont modifiés pour prendre en compte l'effet de la stabilisation magnétique, la précision est meilleure.

EXPERIMENTELLE UND THEORETISCHE UNTERSUCHUNG DES STOFFTRANSPORTS IN MAGNETISCH STABILISIERTEN FLIESSBETTEN

Zusammenfassung—Es wurde der Stofftransport in magnetisch stabilisierten und halbstabilisierten Fließbetten anhand der Vorgänge beim Trocknen von feuchter Luft in Fließbetten aus Aluminium–Stahl-Gemischen experimentell untersucht. Um das Verhalten unterschiedlicher Fließbetten vergleichen zu können, wurden 2 Parameter verwendet, der Fließbettwirkungsgrad und der Wirkungsgrad-Faktor. Zur Überprüfung der Genauigkeit der entwickelten theoretischen Modelle wurden die aus den Experimenten gewonnenen Ergebnisse herangezogen. Während mit Modellen zur Beschreibung der herkömmlichen Fließbettvorgänge keine Übereinstimmung zwischen Theorie und Experiment erzielt werden konnte, wird bei Berkücksichtigung des Einflusses der magnetischen Stabilisierung in diesen Modellen die Übereinstimmung sehr viel besser.

ИССЛЕДОВАНИЕ И МОДЕЛИРОВАНИЕ МАССООБМЕНА В МАГНИТО СТАБИЛИЗИРОВАННЫХ ПСЕВДООЖИЖЕННЫХ СЛОЯХ

Аннотация—Изучался массообмен в магнито стабилизированных и полустабилизированных слоях в процессе сушки влажного воздуха в смесях сталь–алюминий. Различные слои сравнивались по двум параметрам: эффективности слоя и коэффициента эффективности. Полученные данные позволили оценить точность разработанных теоретических моделей. Выяснилось, что классические модели псевдоожиженного слоя расходятся с экспериментальными данными. Однако их модификация с учетом влияния магнитной стабилизации значительно повышает точность.