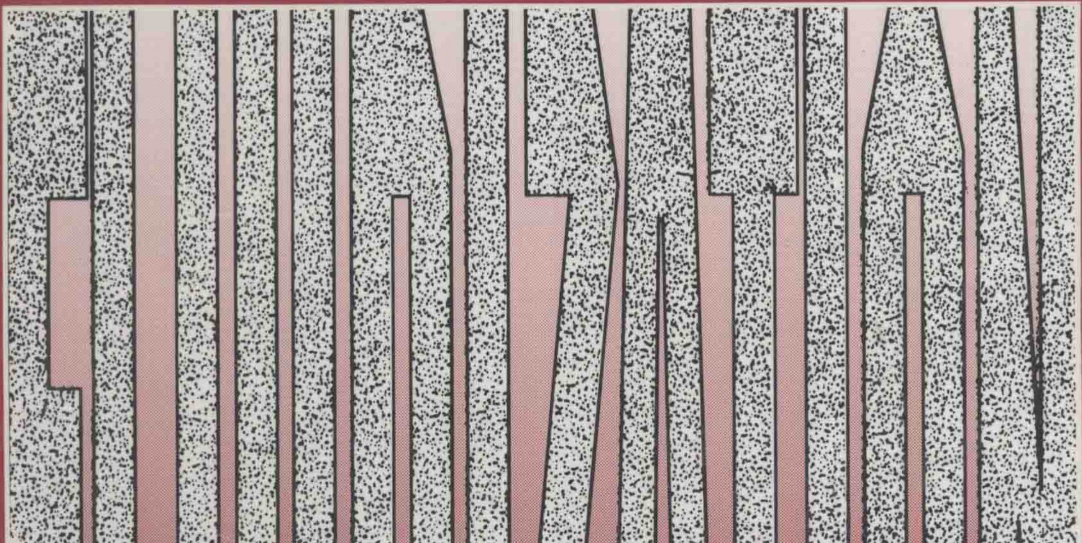

FLUIDIZATION VI

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Engineering Foundation

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PREFACE

Although fluidized beds have been used widely in industry since the 1940's, there continue to be many unsolved questions associated with their behaviour and application. Most of these questions are addressed to one degree or another in this volume. The papers published here have survived an extensive reviewing and revision process, and are drawn from 200 abstracts submitted in response to a call for papers for the International Fluidization Conference held in Banff, Canada from May 7-12, 1989. This is the sixth in a series of such conferences held under the auspices of the Engineering Foundation. Previous conferences in the series have been held in Pacific Grove, U.S. (1975), Cambridge, England (1978), Henniker, U.S. (1980), Kashikojima, Japan (1983) and Elsinore, Denmark (1986). Earlier International Fluidization Conferences were also held in Eindhoven, Netherlands (1967) and Toulouse, France (1973). Each of these conferences has led to a volume like this one. Collectively, these volumes constitute one of the primary sources of information on fluidization and fluid-particle systems.

In selecting papers for the present volume, we have attempted to include papers which emphasize new applications or current major concerns in the field of fluidization. This is reflected in papers which treat advanced materials processing, biochemical fluidized bed reactors, erosion of in-bed tubes, circulating fluidized beds, and attrition and agglomeration of particles. At the same time, we have endeavored to include papers presenting new information in a wide variety of topics which have been covered at previous conferences. We are indebted to Dr. Amos Avidan of Mobil Oil Research who has helped to assemble a number of papers on catalytic cracking, an area which has been under-represented at previous conferences despite its historical and practical importance in the field of fluidization. We have also striven to include papers from most of the major fluidization research groups and from a wide geographical distribution of countries. The fluidization community is truly an international one, and the Engineering Foundation conferences have emerged as the foremost medium for assembling experts from industry, universities and government laboratories to consider the complete range of applications and fundamental problems related to fluidized beds.

The papers in this volume correspond to the material presented in the formal sessions of the conference. Each paper has been limited to eight pages, except that permission was given in a small number of cases to use ten pages where the quality of the paper would have suffered unduly by being limited further. Two invited papers given at the conference and one review paper are being published separately in journals. In order to ensure that the volume is available at the conference itself, we have had to adopt a strict schedule, and this has helped us to assure that the volume, when published, is as current as possible. Unfortunately, postal problems in France caused several papers to arrive so late that they had to be put at the end, out of their preferred sequence.

We wish to acknowledge the support of Harold Comerer of the Engineering Foundation in organizing the conference and supporting this volume. Members of the international working party, especially Dale Keairns and John Matsen, have also assisted us in preparing this conference as has L. S. Fan. We are also grateful to fellow members of the Canadian organizing committee: Ben Anthony, Michael Avedesian, Prabir Basu, Henry Becker, Jan Beeckmans, Leo Behie, Franco Berruti, Cedric Briens, Andre Chamberland, Jamal Chaouki, Claude Chavarie, Lucia Cheung, Michael Couturier, Hugo deLasa, Norman Epstein, Sherrill Grace, John Hazlett, Robert Miller, Song Sit, Bill Svrcek and Kelly Thambimuthu.

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ESTIMATION OF DENSE BED VOIDAGE IN FAST AND SLOW FLUIDIZED BEDS OF FCC CATALYST

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ABSTRACT

A simple expression to estimate FCC dense bed voidage has been derived: $\varepsilon_{BED} = (U+1)/(U+2)$. The expression applies to fast and "slow" beds of FCC catalyst over a range of superficial velocities from near zero up to at least 5 m/s.

A reasonable estimate of dense bed voidage (hence, dense bed density) is important for FCC inventory control, process modeling, and pressure balance calculations. Measured values for dense bed voidage are often unavailable and/or unbelievable. This work derives a simple expression to enable process engineers to estimate dense bed voidage within ±10%.

Superficial velocity in FCC units can vary from 0.1 to 2 m/s as illustrated below:

FCC Strippers: 0.1 m/s to 0.3 m/s
FCC Reactor Beds: 0.6 m/s to 0.9 m/s
Conventional FCC Regenerators: 0.6 m/s to 0.9 m/s
High Efficiency FCC Regenerators: 1 m/s to 2 m/s

FCC strippers, reactor beds, and conventional regenerators are dense beds. High efficiency FCC regenerators have a lower dense bed and an upper dilute (entrained) bed.

THEORY

By a simple volume balance, the dense bed density (ρ_{BED}) in any fluidized bed is given by:

$$\rho_{BED} = \rho_P\ (1-\varepsilon_{BED}) = \rho_P\ (1-\varepsilon_D)(1-\varepsilon_V) \qquad (1)$$

where ε_{BED} is the overall bed voidage, ε_D the dense phase interstitial voidage and ε_V the gas void voidage.

The particle density (ρ_P) is often not quoted for commercial FCC catalysts; instead the Apparent Bulk Density (ABD) is reported.

$$ABD = \rho_P\ (1-\varepsilon_{ABD}) \tag{2}$$

where ε_{ABD} is the interstitial voidage during the ABD test. Data from 16 commercial equilibrium FCC catalysts (Fig. 1) show that there is scatter in values for ε_{ABD}, but a value of 0.4 is a good approximation in Chevron's ABD test equipment. The effect of fines level on ε_{ABD} is outweighed by scatter. Equation (2) becomes:

$$\rho_P = ABD/0.6 \tag{3}$$

To predict ρ_{BED} and ε_{BED} we need values for ε_D and ε_V.

Dense Phase Interstitial Voidage (ε_D)

Since FCC catalyst is a Geldart (1) Group A powder, the voidage at minimum bubbling (ε_{mb}) is greater than the voidage at minimum fluidization (ε_{mf}). As a first approximation we assume:

$$\varepsilon_D = (\varepsilon_{mf}+\varepsilon_{mb})/2 \tag{4}$$

From Abrahamsen and Geldart (2)

$$\varepsilon_{mf} = 1.005\ \varepsilon_{ABD} \tag{5}$$

As ε_{mf} and ε_{ABD} are almost equal, assume that:

$$\varepsilon_{mf} = 0.4 \tag{6}$$

A value of 0.4 is consistent with Dry et al. (3) work which quotes ε_{mf} values from 0.37 to 0.46 for FCC catalyst.

To calculate ε_{mb}, we can use Abrahamsen and Geldart (2):

$$\varepsilon_{mb} = 1-[(1-\varepsilon_{mf})(U_{mf}/U_{mb})^{0.22}] \tag{7}$$

Typical FCC catalyst ranges are: fines content (0 to 45 microns) 5 to 20 wt %, ABD 750 to 1000 kg/m^3, Average Particle Size 60 to 80 microns. From Abrahamsen and Geldart (2) for (U_{mb}/U_{mf}):

$$2.5 < U_{mb}/U_{mf} < 4.6 \tag{8}$$

Plugging in this range of values into Eq. (7) gives:

$$0.51 < \varepsilon_{mb} < 0.57 \tag{9}$$

On average $$\varepsilon_{mb} = 0.54 \tag{10}$$

Then $$\varepsilon_D = (0.4+0.54)/2 = 0.47 \tag{11}$$

In round numbers a good general estimate for ε_D would appear to be:

$$\varepsilon_D = 0.5 \tag{12}$$

This is consistent with Barreto et al. (4) who gave ε_D values in the 0.43 to 0.51 range for FCC catalyst.

Gas Void Voidage (ε_V)

By analogy to the common expression for bubble voidage:

$$\varepsilon_V = (U-U_D)/(U-U_D+U_V) \tag{13}$$

But U_D (the superficial gas velocity percolating through the dense phase) is very small for FCC catalysts (less than 0.002 m/s) compared to FCC operating velocities (0.1 to 2 m/s). Equation (13) becomes:

$$\varepsilon_V = U/(U+U_V) \tag{14}$$

From Eq. (1): $$(1-\varepsilon_{BED}) = (1-\varepsilon_D)(1-\varepsilon_V) \tag{15}$$

Using Eq. (12) and (14) this condenses to:

$$\varepsilon_{BED} = 1-(1-\varepsilon_D)(1-\varepsilon_V) \tag{16}$$

$$\varepsilon_{BED} = 1-(1-0.5)(1-[U/(U+U_V)]) \tag{17}$$

$$\varepsilon_{BED} = (U+0.5U_V)/(U+U_V) \tag{18}$$

Dense Bed Voidage (ε_{BED})

Avidan and Edwards (5) suggest that beds of FCC-type material move into the turbulent regime at superficial velocities in excess of 0.3 m/s. Once in the turbulent regime, the physical meaning of U_V ("average" gas void rise velocity) is unclear. For now, we shall use U_V as a correlating parameter only.

Figure 2 shows the sensitivity of Eq. (18) to various values of U_V over the superficial velocity range of interest in commercial FCC. If U_V is less than 1 m/s, predictions would be substantially thrown off by imprecise values for U_V. However, for U_V greater than 1.5 m/s, significant errors in U_V have only a minor impact.

Using Eq. (1), (2) and (18), values of U_V for commercial FCCs have been back calculated from plant bed density data. Figure 3 gives the values of U_V from FCC vessels that range in size from 3 to 16 meters in diameter. There is a fair degree of scatter (it is plant data after all), but U_V is typically greater than 1.5 m/s--in the range where Eq. (18) is insensitive to U_V. Approximately:

$$U_V = 2 \text{ m/s} \tag{19}$$

Substituting into Eq. (18) gives (in SI units):

$$\varepsilon_{BED} = [U+0.5(2)]/[U + 2] \tag{20}$$

$$\varepsilon_{BED} = (U+1)/(U+2) \tag{21}$$

This simple expression for ε_{BED}, renders simple expressions for dense bed density. From Eq. (1) and (2) (in SI units):

$$\rho_{BED} = \rho_P\ (1-\varepsilon_{BED}) = \rho_P\ [1-(U+1)/(U+2)] \tag{22}$$

$$\rho_{BED} = \rho_P/(U+2) \tag{23}$$

$$\rho_{BED} = ABD/[0.6(U+2)] \tag{24}$$

VALIDITY OF $\varepsilon_{BED} = (U+1)/(U+2)$

The ability of Eq. (21) to predict ε_{BED} for FCC catalyst is tested in Figure 4 against over 100 experimental points from seven literature publications--the number inside each experimental point is the reference number in the literature cited section.

A full 75% of the experimental data is predicted within ±10% by Eq. (21). This is particularly satisfying since Eq. (21) was developed from commercial FCC data (3 to 16 meter diameter vessels) and the experimental data in Figure 4 is for beds 0.305 meter diameter and smaller at velocities up to 5 m/s. Even though the effects of FCC fines on ε_{BED} is not predicted by Eq. (21), over the practical range of fines, data falls close to the ±10% band.

Chevron process engineers have found Eq. (21) a simple and useful estimator of dense bed voidage in FCC strippers, reactor beds, and conventional regenerators. Researchers may find Eq. (21) useful to estimate lower dense bed voidage in CFB's of FCC catalyst.