DOE/PC/94210--T3

Pressure Fluctuations as a Diagnostic Tool for Fluidized Beds

Technical Progress Report for the Period
July 1, 1995 - September 30, 1995

Principal Investigator: Robert C. Brown
Research Assistant: Ethan Brue

Iowa State University
Ames, IA 50011

Work Performed Under Grant
No. DE-FG22-94PC94210

Date Transmitted: October 6, 1995

Prepared for: U.S. Department of Energy
Pittsburgh Energy Technology Center
Pittsburgh, PA

Pressure Fluctuations as a Diagnostic Tool for Fluidized Beds

Technical Progress Report for the Period
July 1, 1995 - September 30, 1995

Principal Investigator: Robert C. Brown
Research Assistant: Ethan Brue
Iowa State University
Ames, IA 50011

Abstract

Comprehensive experimentation has been conducted to determine whether circulating fluidized bed (CFB) pressure fluctuations can be used to verify that similitude conditions in circulating fluidized beds have been achieved. Using two geometrically similar CFB models, pressure fluctuations were recorded while the full set of similitude parameters were matched under a broad range of operating conditions. The method of data acquisition and analysis is shown to be very important in order to observe the significant frequency phenomena. Under relatively dilute conditions similar power spectral density and Bode plot profiles are observed in the two geometrically similar beds. The dominant frequency under these dilute conditions is inversely proportional to the characteristic CFB dimension. Under conditions of higher solids loading, an additional lower bed frequency phenomena is observed in the spectrum which may be a function of the depth of the lower dense bed in the CFB. It is evident from the results that under some operating conditions, a single dimensionless frequency is not sufficient to validate the achievement of similitude using pressure fluctuations. The results also suggest that the use of similitude parameters as they are currently defined is limited to dilute operating conditions, prior to the formation of a lower dense CFB.

Pressure Fluctuations as a Diagnostic Tool for Fluidized Beds

Robert C. Brown and Ethan Brue

Objective

The purpose of this project is to investigate the origin of pressure fluctuations in fluidized bed systems. The study will asses the potential for using pressure fluctuations as an indicator of fluidized bed hydrodynamics in both laboratory scale cold-models and industrial scale boilers.

Progress

Motivation for similitude experimentation

Similitude theory has the potential to become an important tool for fluidized bed design and operation, since the complexity of fluidized bed hydrodynamics makes the development of general theoretical relations difficult. Using dimensional analysis and non-dimensional equations of motion, Glicksman and others derived similitude parameters for bubbling fluidized bed systems [1]. Glicksman extends his analysis to circulating fluidized beds by adding a dimensionless solids flux group to the required similitude parameters [2]. Numerous researchers have matched these parameters in geometrically similar cold-model fluidized beds or have tried to match model conditions in larger scale fluidized bed combustors. Researchers have used a number of techniques to verify that the matching of similitude parameters results in similar hydrodynamics. Typically for CFBs, axial voidage profiles are created from static pressure measurements along the riser. If these axial voidage profiles match, the local solids concentration at any location in the riser should be equal. Other studies have used the probability density function (PDF) of static pressure measurements in fluidized beds to match the distribution of pressure measurements obtained at various locations in the bed [3].

A number of similitude studies have compared the structure of pressure fluctuations in fluidized beds using Bode plots and power spectral density (PSD) functions to verify that hydrodynamic similitude has been achieved [4-6]. However, the validity of pressure fluctuation analysis for verifying similitude in fluidized bed models and industrial scale boilers cannot be assumed until a better understanding of the complex structure of pressure fluctuations is achieved. This study focuses on pressure fluctuation analysis as a method for similitude verification, outlining how pressure fluctuations should be analyzed and qualitatively describing the hydrodynamic information contained in these fluctuations.

Experimental apparatus for similitude experiments

This study was performed in two geometrically similar cold-flow CFB models. The riser of the larger unit is 0.102 m in diameter and 3 m tall. This unit is fluidized with 0.2 mm, 0.3 mm, and 0.4 mm diameter glass beads. Pressure taps are located at 25.4 cm intervals along the riser to measure pressure fluctuations using a Schaevitz P3061-10WD pressure transducer. The smaller unit was a one-half scale model of the larger unit. The smaller CFB was fluidized with 0.1 mm, 0.15 mm, and 0.2 mm diameter steel shot. The large bed was fluidized with air at atmospheric pressure. The small bed was fluidized with air at pressures of 28.3 psig (195 kPa gage). The small bed was operated at superficial velocities ranging from 2 to 4 m/s and solids flux of 20 to 50 kg/m^2s. The large bed was operated at superficial velocities of 3.3 to 5.7 m/s and solids flux of 10 to 24 kg/m^2s.

Pressure fluctuations between selected pairs of pressure taps were typically recorded at a 20 Hz sampling frequency to obtain 70,000 data points per run. Preliminary tests at sampling frequencies up to 140 Hz were performed to insure that high frequency phenomena were not being overlooked and aliasing was not occurring. It is important to recognize that as the sampling frequency increases the number of points describing the important low frequency characteristics decreases. For an ergotic random process the power spectral density can be calculated as:

$$PSD(n) = E[FFT(n) \cdot FFT^*(n)] \quad (1)$$

using an FFT algorithm for N data points where n = 0,1,2...,N-1 and FFT*(n) denotes the complex conjugate of FFT(n). E is the expected value operator [7]. It is important for accurate spectral information that the expected value operator is included in the spectral analysis by averaging multiple realizations of the data set. In this study, the data were analyzed by dividing each run into 15 data segments of 8192 and taking the fast Fourier transform (FFT) of each segment. These 15 data sets are averaged to produce a smooth characteristic power spectral density for the run. A Bode plot, convenient for establishing the order of linear models and estimating their parameters, is produced by plotting 10 log (PSD) vs. log ω where ω is the angular frequency in radians per second.

Spectral analysis results

Before a complete set of similitude experiments could be performed to compare pressure fluctuation data, a proper spectral analysis methodology had to be carefully devised. The developed methodology insured that all important fluctuation information was observed in the spectrum. A series of tests were conducted to determine how many data points were necessary to create a representative pressure fluctuation spectrum. Figures 1-2 and Figures 4-5 contrast the results of two different methods of analysis used in previous studies [7,9]. In Figures 1 and 2, it is demonstrated that matching Bode plots under conditions of similitude using such small data sets is inconclusive. In Figure 1, similitude parameters are matched and the Bode plots look very similar. Figure 2 shows the Bode plots of experiments not conducted under similitude conditions. Again the Bode plot profiles match very well. In the Bode plots of properly analyzed pressure fluctuations (Figures 3-4), the details of the pressure fluctuation structure as described in previous studies is evident [8,9]. There is a marked difference between the spectral plots of 1024 data points sampled at 100 Hz with 4 set averaging (Figures 1 & 2) and the spectral plots of 70,000 data points sampled at 20 Hz with 15 set averaging (Figures 3 & 4). Figure 3 does show that similar Bode plot profiles are observed when similitude parameters are matched under dilute conditions.

CFB similitude test results

After demonstrating the importance of careful analytical methods, a comprehensive similitude study was conducted in the large and small CFB, as outlined in Table 1. A number of conclusions can be drawn from these results. First, when similitude conditions are matched for low solids loading conditions, the Bode plot profiles are very similar over the entire length of the bed (See Figure 3). The dominant frequency is related to the inverse square root of the characteristic CFB dimension and must be non-dimensionalized accordingly. As the solids loading is increased, the matching of similitude parameters no longer results in similar pressure fluctuation Bode plots at all elevations in the bed. While the upper dilute region may exhibit a similar pressure fluctuation structure in both the large and small CFB, the lower dense bed fluctuations are not identical (see Figure 4).

In the case of very high solids loading, the lower CFB Bode plot profiles in the large and small CFB are observed to be similar, but the dominant frequency observed in both beds do not always match when non-dimensionalized according to the inverse square root of the characteristic CFB dimension. In other words, two different phenomena manifest themselves in the upper dilute and lower dense sections of CFBs. The lower bed fluctuations appear to be a function of the lower dense bed height and are not governed by the same phenomena as the upper dilute region.

The final observation in these similitude tests is that as the solids loading increases, the axial voidage profiles in the large bed consistently show a more dense lower bed than the small CFB (see Figure 5). Also, as operating conditions approach a maximum solids loading condition, experiments conducted in the small CFB could not be matched in the large CFB, since the large CFB reached the choking condition sooner. This suggests that the rate of solids flow downward in the riser is a very important consideration in CFB hydrodynamic behavior. As the diameter of the bed increases, so does the amount of material moving downward in the outer annulus. This variable is not considered in the standard set of CFB dimensionless parameters. Since the dimensionless variables are derived from non-dimensionalized equations of motion assuming a simple dilute phase behavior, the matching of similitude parameters under dilute operating conditions do result in similar hydrodynamics.

Conclusions and future work:

Previous studies that have attempted to use spectral analysis of CFB pressure fluctuations to verify the achievement of similitude have not taken sufficient data to observe CFB system characteristics in the PSD plots or Bode plots. We have shown that significantly larger data sets must be analyzed and averaged in order to draw valid conclusions on whether CFB pressure fluctuation structure validates the proposed similitude parameters. The completion of the similitude experimentation suggests that the similitude parameters as they are currently defined are only valid under dilute operating conditions.

Future work will investigate the possibility of extending the dimensionless parameters such that they can be used to describe CFB system hydrodynamics even under dense bed conditions. Currently, preparations are being made to take additional pressure fluctuation measurements at the ISU CFB boiler. This data will confirm whether the observed pressure fluctuation structure in cold models can be also observed in industrial scale units.

Works Cited

[1] Glicksman, L.R. "Scaling relationships for fluidized beds." *Chem. Eng. Science* 1984, 30(9), 1373-1379.

[2] Glicksman, L.R., D. Westphalen, K. Woloshun, T. Ebert, K. Roth, and M. Lints. "Experimental scale models of circulating fluidized bed combustors." *Fluidized Bed Combustion, ASME* 1991; 1169-1174.

[3] Louge M, and H. Chang. "Fluid dynamic similarity of circulating fluidized beds" *Powder Technology* 1992, 70, 259-270.

[4] Glicksman L.R., and M.T. Nicastro. "Experimental verification of scaling relationships for fluidized bed." *Chem. Eng. Science* 1984, 39(9), 1381-1391.

[5] Glicksman, L.R., D. Westphalen, C. Bereton, and J. Grace. "Verification of the scaling laws for circulating fluidized beds." In *Circulating Fluidized Bed*

Technology III. P. Basu, M. Hasatan, and M. Horio, Eds.; Pergamon Press: Oxford, 1991; 199-124.

[6] Glicksman, L. R., M. R. Hyre, and K. Woloshun. "Scale models of circulating fluidized bed combustors." Report # DOE/MC/25049-3372, USDOE, Washington, D. C.

[7] Komo, J.J. Random Signal Analysis in Engineering Systems; Academic Press Inc.: Orlando, 1987.

[8] Brue, E., J. Moore, and R. C. Brown. "Process model identification of circulating fluid bed hydrodynamics." In *Circulating Fluidized Bed IV* conference proceedings. AIChE, 1994.

[9] Brue, E., J. Moore, and R. C. Brown. "Wave phenomena in circulating fluidized beds." In *1st International Particle Technology Forum* conference proceedings. AIChE, 1994.

Table 1: Similitude experiments outline

#	D/dp ($x10^{-2}$)	H/dp ($x10^{-2}$)	ρ_f/ρ_s ($x10^{4}$)	Re_p	Fr ($x10^{-3}$)	$G_s/\rho_s U$ ($x10^{3}$)
1	1.5	5.1	4.7	40	4.6	1.3
2	1.5	5.1	4.7	40	4.6	1.9
3	1.5	5.1	4.7	40	4.6	2.6
4	1.5	5.1	4.7	47	6.3	1.7
5	1.5	5.1	4.7	47	6.3	2.2
6	1.5	5.1	4.7	47	6.3	2.8
7	1.5	5.1	4.7	54	8.2	1.9
8	1.5	5.1	4.7	54	8.2	2.4
9	1.1	3.4	4.7	71	4.2	1.1
10	1.1	3.4	4.7	71	4.2	1.7
11	1.1	3.4	4.7	81	5.4	1.4
12	1.1	3.4	4.7	81	5.4	1.9
13	1.1	3.4	4.7	81	5.4	2.4
14	1.1	3.4	4.7	95	7.5	1.6
15	1.1	3.4	4.7	95	7.5	2.1
16	0.8	2.5	4.7	108	4.1	1.0
17	0.8	2.5	4.7	108	4.1	1.4
18	0.8	2.5	4.7	126	5.6	1.2
19	0.8	2.5	4.7	126	5.6	1.6
20	0.8	2.5	4.7	126	5.6	2.1
21	0.8	2.5	4.7	148	7.7	1.4
22	0.8	2.5	4.7	148	7.7	1.8

- **Each of the 22 sets of similitude parameters was matched in both the large and small model CFBs.**

Figure 1: Bode plot of LCFB pressure fluctuations under identical conditions (inadequate sampling)

Dotted trace - (Re_p=150, Fr=7700, G_s=$0.98\cdot10^{-3}$)

Solid trace - (Re_p=150, Fr=7700, G_s=$0.98\cdot10^{-3}$)

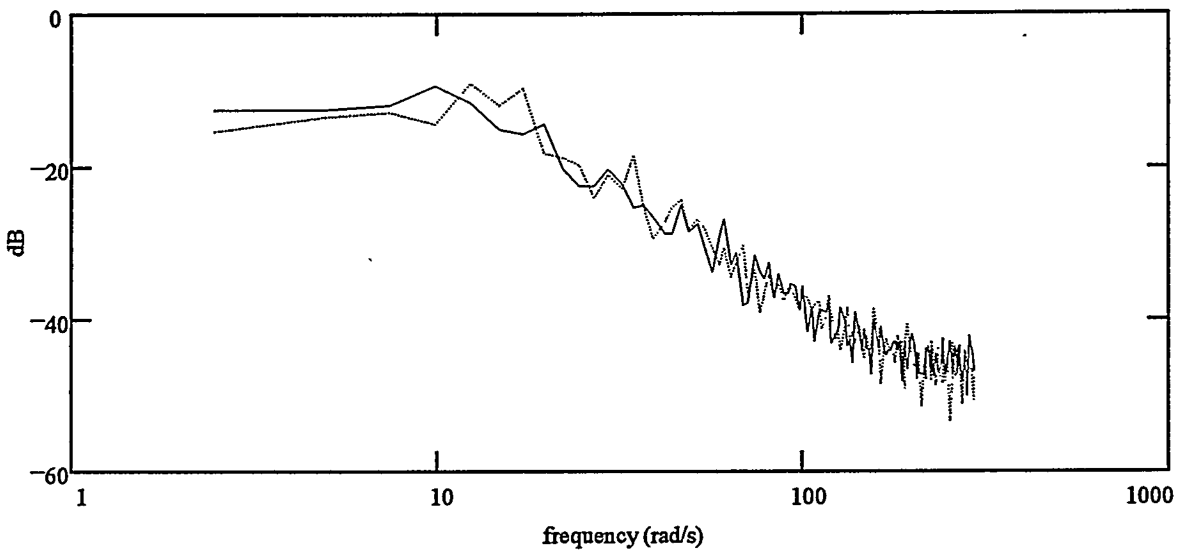


Figure 2: Bode plot of LCFB pressure fluctuations under non-similitude conditions (inadequate sampling)

Dotted trace - (Re_p=108, Fr=4100, G_s=$2.3\cdot10^{-3}$)

Solid trace - (Re_p=150, Fr=7700, G_s=$0.98\cdot10^{-3}$)

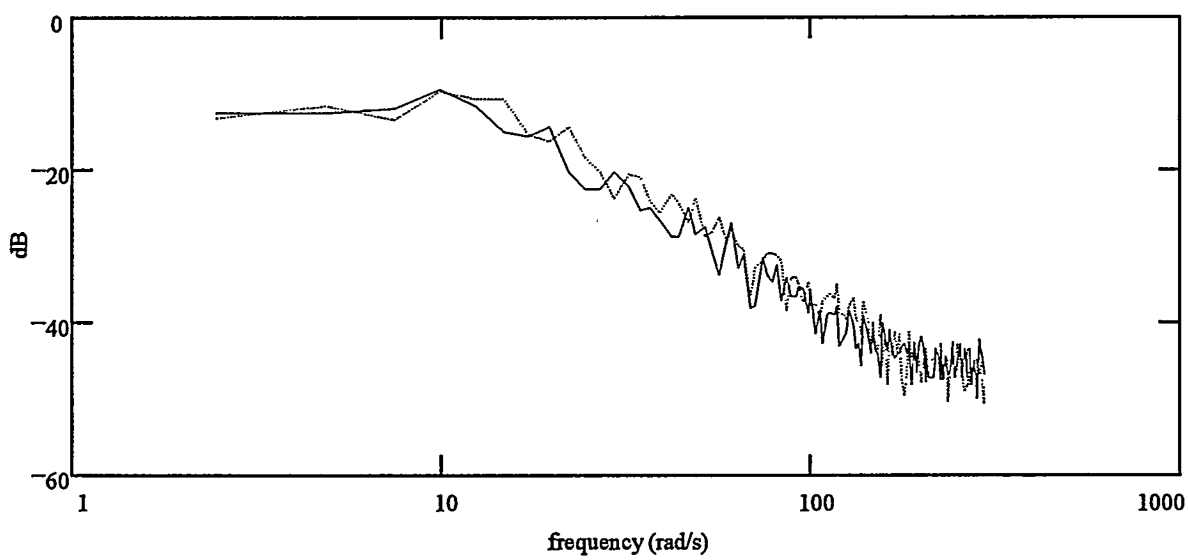
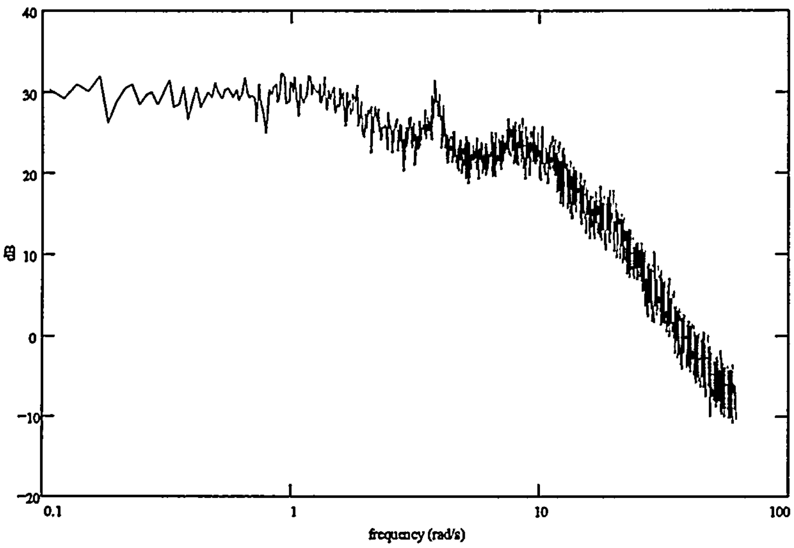


Figure 3: CFB Bode plots under conditions of similitude
Low solids loading
Static pressure fluctuations measured at 75% bed height

Small model CFB:
$Re_p = 109 \pm 10$ $G^* = 9\cdot10^{-4} \pm 2\cdot10^{-4}$
$Fr = 3900 \pm 300$ $\rho s/\rho g = 2150 \pm 25$



Large model CFB:
$Re_p = 108 \pm 6$ $G^* = 10\cdot10^{-4} \pm 2\cdot10^{-4}$
$Fr = 4100 \pm 300$ $\rho s/\rho g = 2150 \pm 70$

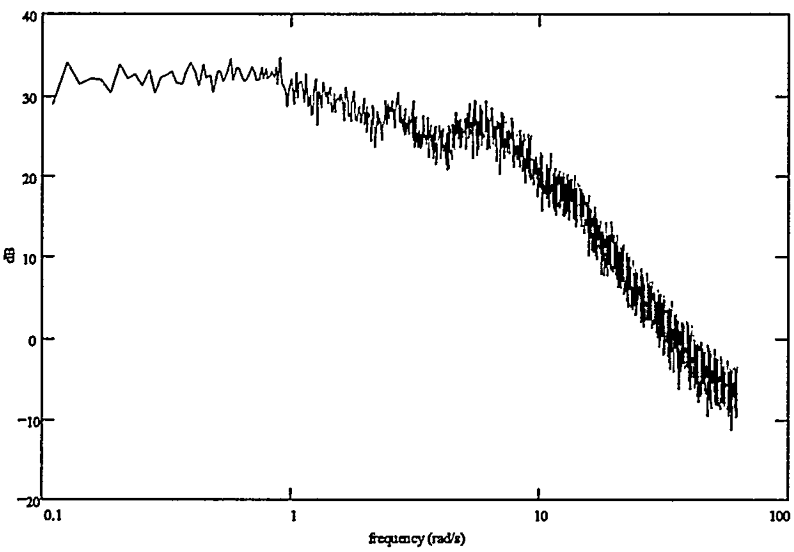
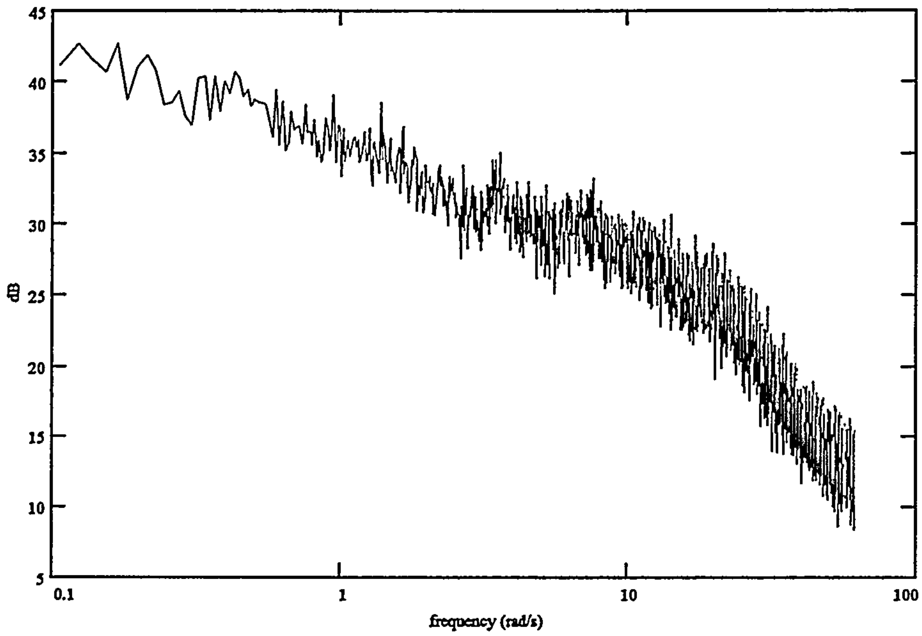


Figure 4: CFB Bode plots under conditions of similitude
High solids loading
Static pressure fluctuations measured at 5% bed height

Small CFB model:



Large CFB model:

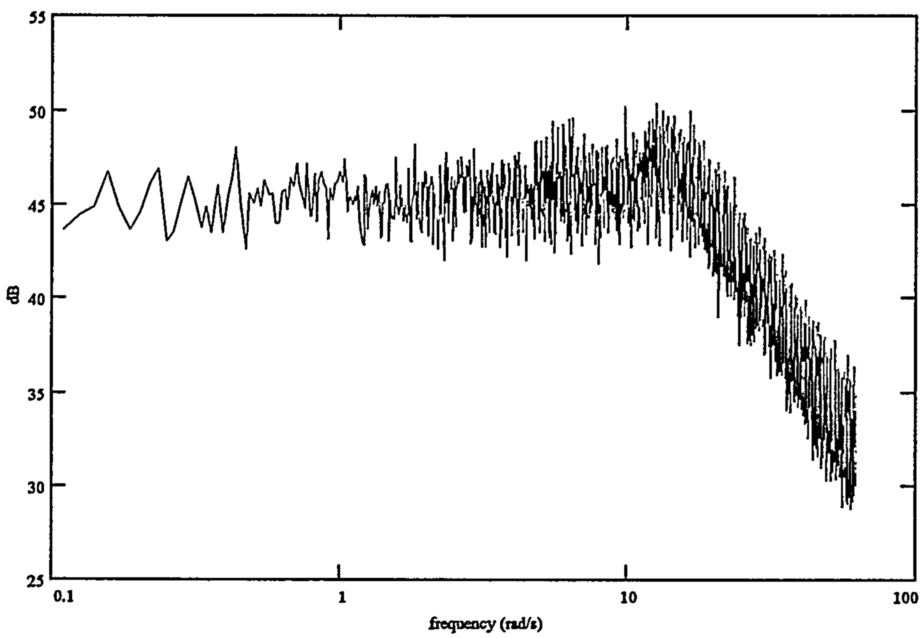
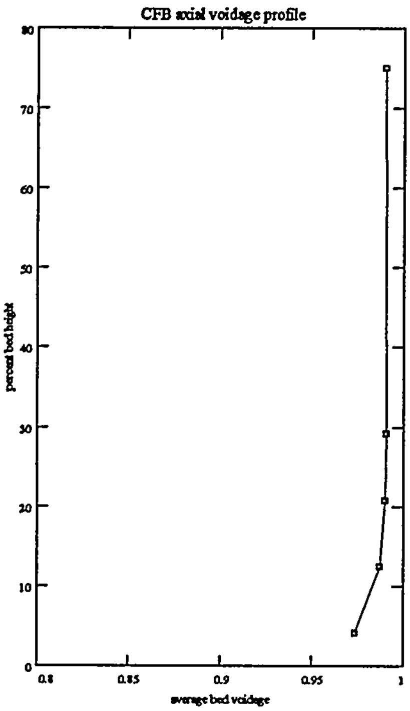


Figure 5: CFB axial voidage profiles under conditions of similitude
High solids loading

Small CFB model
Rep = 83 ± 10
Fr = 5500 ± 800
G*= $1.4 \cdot 10^{-3} \pm 2 \cdot 10^{-4}$
$\rho s/\rho g = 2160 \pm 30$



Large CFB model
Rep = 81 ± 4
Fr = 5500 ± 400
G*= $1.3 \cdot 10^{-3} \pm 2 \cdot 10^{-4}$
$\rho s/\rho g = 2150 \pm 70$