PRESSURE FLUCTUATIONS IN GAS FLUIDIZED BEDS

by

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The pressure fluctuations in a fluidised bed are a result of the actions of the bubbles. However, the bubbles may be influenced by the air supply system and by the pressure drop of the air distributor. These interactions are treated for low as well as for high velocity beds by means of a simple model of the principal frequency of the pressure fluctuations. The model includes the interaction with the air supply system and describes qualitatively two important bubbling regimes: the single bubble regime, important for systems with low pressure drop air distributors, and the exploding bubble regime for high velocity beds.

Key words: fluidized beds, bubbles, pressure fluctuations, air distrib-utors, air suply system

Introduction

The pressure fluctuations in a fluidised bed are related to the movements of the bed and particularly to the bubbles. This subject has been thoroughly investigated in the past, but there are reasons to continue the exploration of pressure fluctuations. Firstly, during recent years computers and data collection equipment have made registration of pressure signals and evaluation of data a relatively simple task. Secondly, available analyses were dedicated to bubbling conditions at low fluidisation velocities, but the present interest also covers circulating fluidised beds (CFB). Pressure fluctuations in CFB have been studied to characterise the state of fluidisation. As the amplitude of pressure fluctuation increases during a rise of velocity, the CFB may pass several fluidisation regimes, such as slugging, turbulent and fast fluidisation, the latter regime being characterised by rather smooth conditions without bubbles. It appears that the CFB studies mentioned were carried out in high aspect ratio (bed height to bed width ratio) risers. In contrast, studies carried out in low aspect ratio risers, such as combustors, observed a behaviour reminding of a bubbling bed also at high gas velocities [1, 2]. Therefore, there is a reason to account for the fluidisation behaviour under various conditions, including those of bubbling CFB, by means of pressure analysis. The purpose of the present paper is to illustrate the fluidisation behaviour as seen from bed pressure fluctuations and to study the interaction with the gas volume below the bed.
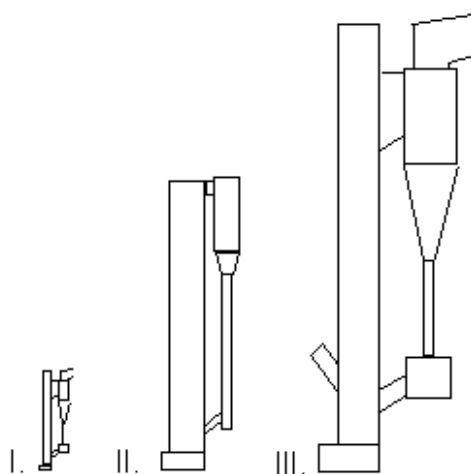
Figure 1. The experimental equipment

Experimental conditions

Measurements were carried out in three plants of different scale and design, Fig. 1. The absolute pressure was sampled from the dense bottom bed and from the air plenum below the air distributor. The properties of the three plants are listed in Table 1. Plant III is a 12 MW boiler described by Leckner *et al.* [3]. Plant I is a 1:9 cold scale model of the boiler. Johnsson *et al.* [4] made a closer description of this plant and explained the scaling conditions. Plant II is a cold CFB laboratory rig with rectangular cross section. The size of the air supply system, and particularly of the air plenum, can be important for the pressure fluctuations. Therefore the air supply systems are shown roughly in Fig. 2.
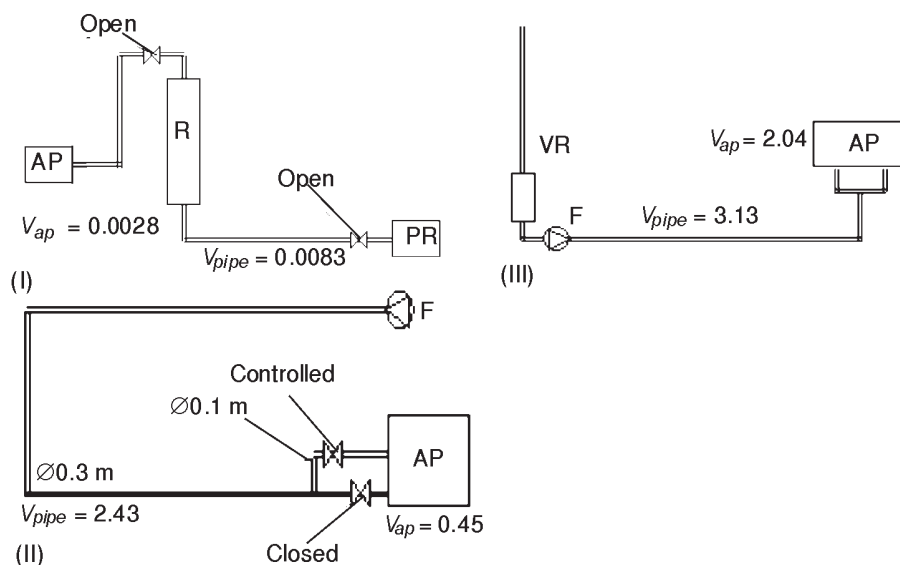

Figure. 2. Air-feed systems (not scaled) in plants I, II, and III. F – fan, AP – air plenum, PR – pressure reducer of pressurized air system, R – rotameter, VR – velocity reducing volume, V_{ap} – volume of air plenum, [m³], V_{pipe} – volume of air-feed pipes downstream of PR in I and F in II and III

Table 1. Data of the research plants

| Quantity	Plant I	Plant II	Plant III
Cross section, A_{bed} [m²]	0.16×0.19	0.12×0.70	1.47×1.42
Height of riser, [m]	1.5	8.5	13.5
Volume of air plenum, V_{ap} [m³]	0.0028	0.45	2.04
Total volume of air supply system including pipes and air plenum, V_t [m³]	0.0111	2.88	5.17
Air distributor	perforated plate	perforated plates	bubble cap
Bed temperature, [°C]	40	40	40, 850
Fluidisation velocity, U [m/s]	0.4 to 1.4	0.4 to 1.8	0.3 to 6.0
Bed material	iron	silica sand	silica sand
Mean particle size, d [mm]	0.06	0.32	0.15 to 0.43
Particle density, ρ_p [kg/m³]	7860	2600	2600
Height of dense bottom bed, H [m]	0.06	0.2 to 0.8	0.2 to 0.8

Experimental results

The quality of fluidisation was studied systematically in Plants II and III. As a result, Svensson *et al*. [5] identified three fluidisation regimes: multiple bubble regime, single bubble regime and exploding bubble regime. In the *multiple bubble regime* numerous small bubbles are formed in the bed. This is reflected in the wide range of frequencies seen in the pressure spectrum. There is no correlation between the pressure fluctuation in the bed and in the air plenum. The distributor pressure drop is high. In the *single bubble regime* the bed is bubbling with large, regular bubbles, producing a narrow frequency spectrum. This regime occurs at a combination of low pressure-drop distributor and low fluidisation velocity. At high velocities bubbles become large. They look like irregular voids, whose size is limited by the height of the dense bottom bed. This is the *exploding bubble regime*.

Figure 3 shows an example of a gradual transition between the multiple bubble regime (a) and the single bubble regime (c) as the pressure drop across the distributor dp_{dist} is reduced at constant fluidisation velocity U = 0.4 m/s. In these tests the ratio dp_{dist}/dp_{bed} ranged from 0.04 to above one, but the operation was deemed satisfactory in all cases, although the character of fluidisation changed depending on the pressure drop. The dominant frequency of the wind box pressure was about 0.8 Hz in all tests shown in Fig. 3. Obviously, the connection between the wind box and the bed was small during operation with the high pressure-drop distributor (a), but in the case of the low pressure-drop distributor (c) there was a direct coupling between bed and wind box. At higher fluidisation velocities in the same Plant II there was a direct connection between bed and wind box also at high pressure-drops, and frequencies slightly higher than 1 Hz were observed. In this case the bubbles had an exploding character.
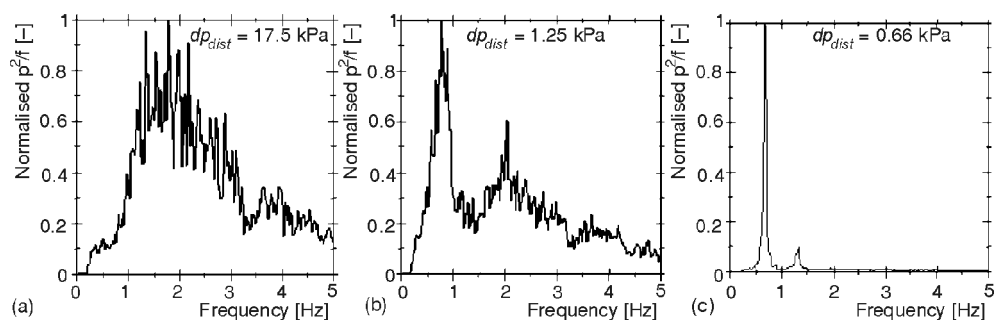
Figure 3. In-bed pressure fluctuation spectra corresponding to a transition from multiple bubbling to single bubble regime in Plant II. $U = 0.4$ **m/s,** $H = 0.6$ **m,** $d = 0.32$ **mm (from [5])**

In the boiler, the same bubble-cap distributor was used in all tests and the velocity was changed. This means that the pressure drop across the distributor also changed. The results are shown in Fig. 4, which illustrates a transition from single bubbling regime (a) to exploding bubbling regime (c) as the velocity increases. The intermediate case (b) in Fig. 4 is a transition case where the two regimes are present, as seen in the frequency domain. A similar occurrence of two regimes was previously shown in Fig. 3b. The advantage of operation under cold conditions, and in a subsequent test under hot conditions in the same unit [5], is that the results and the conclusions could be verified by independent optical fibre measurements. The transition was found also under hot (850 °C) conditions, but it was not possible to operate as low as in the cold case (0.3 m/s), since the same gas flow is (850 + 273)/(40 + 273) times as large in the bed under hot bed conditions. On the other hand, high velocities could be attained. Registrations were carried out up to 3.4 m/s.
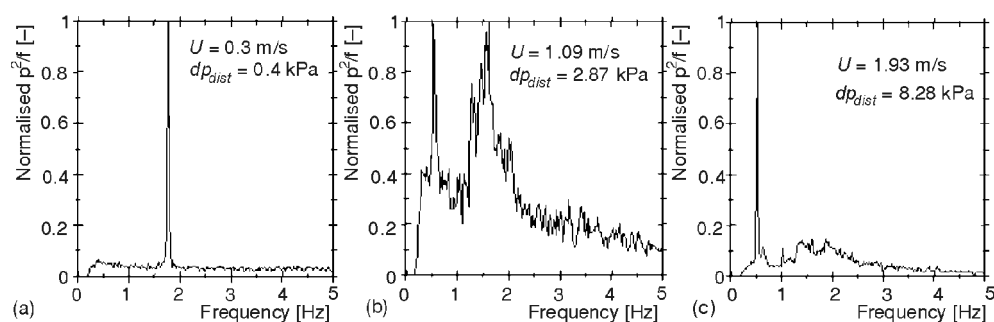
Figure 4. Frequency spectra of pressure fluctuations in Plant III operated under cold conditions. $H = 0.3\text{-}0.4$ **m,** $d = 0.15$ **mm (form [5])**

Interpretation

The various regimes identified have not been explicitly mentioned in the early literature. Many researchers studying bed processes have probably aimed at the high distributor pressure-drop case with multiple bubbles in order to achieve a well-behaved bubbling fluidised bed. However, also conditions similar to the single bubble regime have been observed and described, for instance by Baird and Klein [6], Borodulya *et al.* [7], and Baskakov *et al.* [8]. In the single bubble regime the bed behaves like a piston accelerated by a growing bubble, Fig. 5a. Davidson [9] interpreted this behaviour as an interaction between the bed and the air plenum and derived an expression for the bubble frequency. Many researchers adopted Davidson's idea and also included the resistance of the distributor [10] and the air supply system [7]). For the present purpose it is sufficient to write the bubble frequency as

$$f = \frac{1}{2\pi} \left(\frac{\gamma p A}{\rho H V} \right)^{1/2} \tag{1}$$

where γ is the polytrop coefficient, p mean pressure in the plenum, A bed (piston) surface area, ρ bed density, H bed height, and V is the effective volume of the air supply system. The derivations were made for isothermal systems. In a combustor, the temperature is different in the bed and in the air plenum. Hence, a change of the gas density in the air plenum $\rho_{g,ap}$ is felt in the bed as a corresponding change in the gas density $\rho_{g,bed}$ at bed temperature. A derivation shows that the right hand side of eq. (1) should be multiplied by a factor $(\rho_{g,bed}/\rho_{g,ap})^{1/2}$ to consider non-isotermal cases.

The principal difficulty in applying eq. (1) lies in defining the effective gas volume upstream of the air distributor. Does the volume of the wind box represent the adequate volume V in eq. (1) or is it necessary to include also parts of the ducts of the air supply system? Obviously the pressure pulses from the bed are felt in the entire air supply system in the case when no devices causing pressure drops are present (such as high-pressure air distributor, closed valves, meters *etc*.), Johnsson *et al.* [11]. Here (Fig. 2
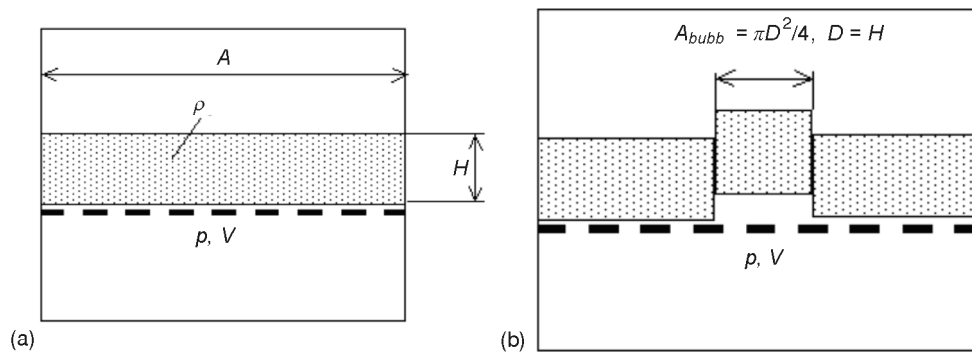

Figure 5. Bubble models for (a) single an (b) exploding bubbles. Bed (grey) and air distributor (dashed)

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and Table 1) both air plenum and the air supply system downstream of some valve could serve as effective air volume, V, but it is not known how much of the air supply system that should be considered effective. Therefore the results are shown below both with and without the air supply system. Another problem consists in defining the effective area of the piston. Above, A was taken to be the area of the bed, A_{bed}. However, for smaller bubbles one could imagine that only a vaguely defined part of the bed would move. In the case of an exploding bubble, the definition of an exploding bubble could be employed, Svensson *et al.* [5], namely that the size of the bubble (D) is limited by the height of the bed, $D \approx H$, and that the bubble opens up for a flow of gas that only lifts the part of the bed where the bubble acts, $A = A_{bubb} = \pi D^2/4$ in a three-dimensional bed. This case is illustrated in Fig. 5b. Once the plug of bed material is lifted, the gas escapes and the rest of the bed may not be affected.

Application

Agreement between the model, eq. (1), and measured frequencies from single bubbles has been demonstrated by Baird and Klein [6], Moritomi *et al.* [10], and Baskakov *et al.* [8], but in view of the uncertainties mentioned, a further discussion is needed. A comparison between measurement data from the three plants and the model is shown in Figs. 6 to 8. The model is represented by two cases: the effective volume is either that of the air plenum or that of the plenum plus air supply system, as shown in Fig. 2 and Table 1. Figure 6 compares the frequencies obtained in the boiler with the model under both hot and cold conditions. The hot case has a hot bed and a cold air supply system (non-isothermal conditions), whereas in the cold case the bed and the air supply system have the same temperature (isothermal conditions). Qualitatively the results
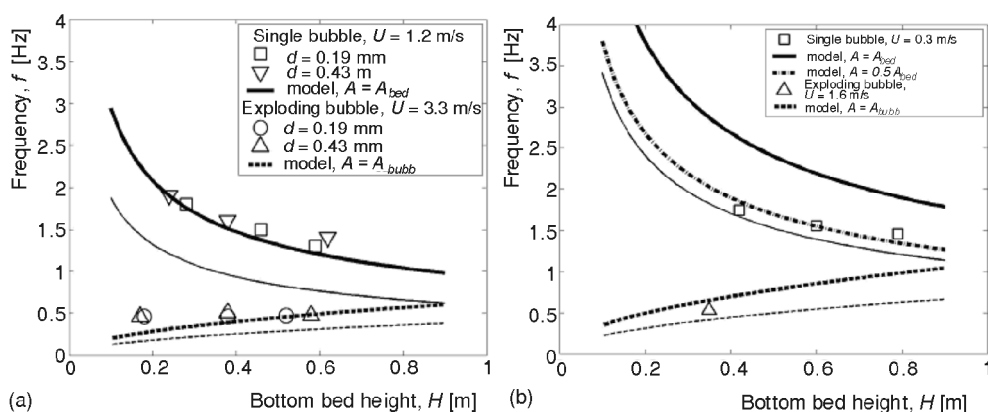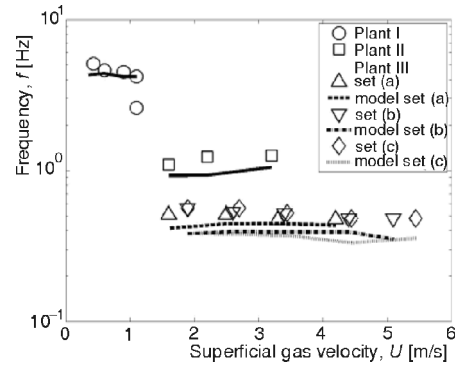

Figure 6. Measured frequencies (symbols) from the boiler, Plant III compared to model (curves), (a) $T = 850$ °C; (b) $T = 40$ °C, $d = 0.15$ mm. The thicker lines correspond to $V = V_{ap}$ and the thinner lines to $V = V_t$

support the model approach: indeed the difference between the single bubbles and exploding bubbles is described by the assumption of different active piston areas in Fig. 5. Within the range of uncertainties there is a systematic difference between single bubbles in the hot (Fig. 6a) and the cold (Fig. 6b) cases: the hot case coincides with $V = V_{ap}$ but the cold case with $V = V_t$. At present it is not possible to explain this difference, but a guess would be that the active areas are different for the high velocity (a) and the low velocity (b) cases of single bubbles, since they actually depend on bubble size, $i.\ e.$ fluidisation velocity. For example, agreement would be obtained if the piston area were equal to half of the bed area in the low-velocity case and the area of the high-velocity case remained unchanged. This case is illustrated in Fig. 6b.
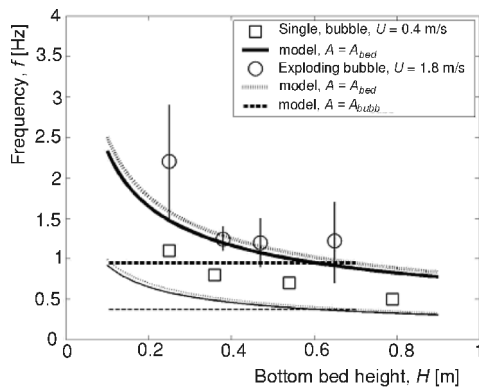
Figure 7. Comparison between measured frequencies (symbols) from Plant II and model (curves). The thicker lines correspond to $V = V_{ap}$ and the thinner lines to $V = V_t$

Figure 8. Measured exploding bubble frequencies (symbols) in Plant I, II, and III (hot) compared to model, $A = A_{bubb}$ (curves), dp_{ref} is reference pressure drop from 0.06 m to 1.5 m above the air distributior. The lines represent $V = V_{ap}$

The corresponding data from the cold rig, Plant II, are shown in Fig. 7. The agreement in Fig. 7 is qualitative, but within or close to the limits of uncertainty. The case of multiple bubbles was not in agreement, and such data are not plotted. (The reason is of course that in this case the bed is insulated from the air plenum by the high pressure-drop distributor.)

In Fig. 8 exploding bubble frequencies from all three plants are compared. For clarity only the curves for $V = V_{ap}$ are drawn. The agreement is again qualitative, but reasonable, since $A = A_{bubb}$ used for modelling the exploding bubbles is an obvious approximation, considering the complex shape of the bubbles. The result is almost independent of velocity, which also agrees with the concept of exploding bubbles. It appears that the principal features of the fluctuations have been captured by the model, which is a severe task, bearing in mind the large differences in size and operation of the plants investigated.

Conclusion

In a previous work three bubbling modes were defined: multiple bubble regime (low velocities, high distributor pressure drop), single bubble regime (low distributor pressure drop) and exploding bubble regime (high velocity). The bottom bed of a CFB boiler produces exploding bubbles that appear like outburst of bed material from the bottom bed. These bubbles are limited in size by the height of the bottom bed and result in a considerable through-flow of gas. (In fact, this is the explanation to why the bed can be maintained in the bottom of the CFB despite the high fluidisation velocity). There is a gradual transition between regimes, and under transition conditions they may occur intermittently during a certain period of observation. Because of the high pressure-drop across the air distributor required for a multiple bubble regime such a regime will not occur in a CFB combustor.

The frequency model describes qualitatively the measured frequencies in the three very different beds investigated. There are two principal reasons for the uncertainty of interpretation: the size of the active volume in a system with air supply ducts and the size of the active area of the bed (the piston). In the exploding bubble case the definition of an exploding bubble can be used to determine the piston area, an approach that agrees with measurements. This gives an indication of the qualitative correctness of the model concept.

Further work is necessary to interpret the variations of the fluctuations, especially the interactions between bed and air supply system, not only in order to learn more about the determination of the effective volume, that caused a considerable uncertainty in the present estimates, but also to understand the impact of fluid transients in the long pipes of the air supply systems. These transients may have a considerable influence on the fluidisation behaviour, but they were not considered in the present work.

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