Microwave Measurement of Density Profiles in Fluidized Bed Reactors with Improved Spatial Resolution

Thorsten Hauschild, Reinhard Knöchel

Technische Fakultät der Christian Albrechts Universität zu Kiel
Lehrstuhl für Hochfrequenztechnik
Kaiserstraße 2, D-24143 Kiel, Germany

Abstract

A technique suitable for measuring density profiles of solids inside an ecologically friendly circulating fluidized bed coal combustor is introduced. Employing a microwave locating reflectometer it is possible to perform measurements in the dense phase of the reactor. Improvement of the spatial resolution by using a pole extraction algorithm is discussed.

1 Introduction

Solid fluidized bed reactors are used in chemical engineering for various applications like drying of solids, reduction of iron oxides or combustion of coal [Kun91]. For optimizing the coal combustion at alternating load conditions it is necessary to know about the concentration of solids at significant positions inside the reactor (see fig. 1). Using existing techniques density is measured by employing mechanical systems or optical reflection sensors [Wer90]. Both techniques disturbe the fluidized bed because they require putting a sensor or mechanical plunger into the reactor.

As a novel application, microwaves are proposed to measure the differences in density. The system is based on a microwave locating reflectometer [Hol69], [Hau93] (see fig. 2). With this measurement setup it is possible to obtain the complex reflection coefficient r_i in dependence of it's location x_i which is coded in a low frequency signal f_i

$$y(t) = \sum_{i=1}^{M} r_i \cdot e^{j2\pi \cdot f_i \cdot t} \quad \text{with} \quad f_i = \frac{B}{T_S} \cdot (t_i - t_r) \ .$$

Using this system a penetration depth up to several meters into the reactor becomes possible at X-band frequencies (8-12 GHz). Due to the given bandwidth B of 4 GHz the axial resolution for density changes is approximately 7 cm without applying special signal processing. The microwave system allows fast measurements in order to determine changes in density due to different load conditions. This task has to be performed quickly because of the dielectric filling of the reactor is moving at speeds up to 1 m/s.

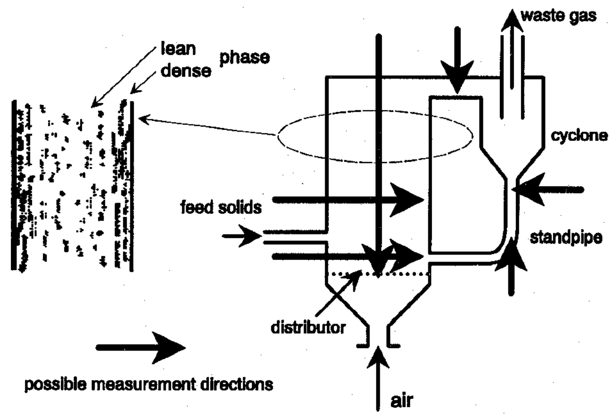

Fig. 1: Important measurement directions inside a circulating fluidized bed reactor and distribution of lean and dense phases in the reactor

For simulations of the density distribution inside the fluidized bed reactor it is necessary to get information about the dielectric agent inside the reactor. Mechanical measurements of the material inside a fluidized bed coal combustor in Kassel/Germany show, that the compound inside the combustor is nearly independent of the measurement place and load state of the combustor. Approximately 30 % volume fraction is lime, 30 % is gypsum, 30 % is sand, 1 % is coal and the rest are other components. The average size of the particles is 200μm. With a very accurate microwave method the dielectric constant of the combustor compound (not

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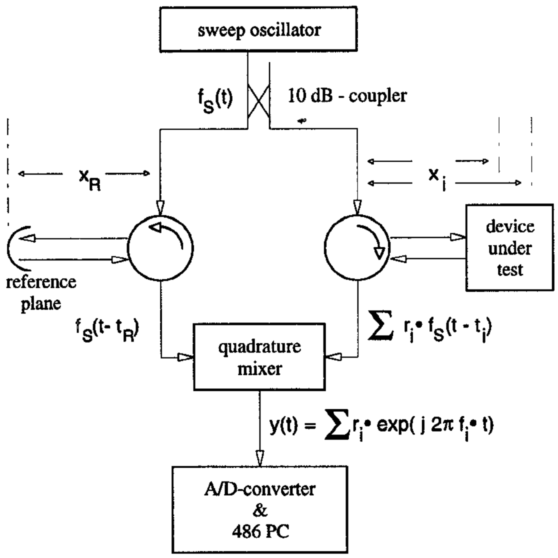

Fig. 2: Microwave locating reflectometer

fluidized) was measured.

The result $\epsilon_r = \epsilon' - j\epsilon'' = 3.14 - j0.012$ is virtually frequency independent in X-band. This value was used to calculate the dielectric constant versus the concentration of solids in air using the empirical law of refractive indices $\sqrt{\epsilon_r} = \sum_i m_i \sqrt{\epsilon_{ri}}$; m_i =volume fraction of the material i.

2 Spatial Resolution

A knowledge of the thicknesses of the dielectric layers inside the reactor with better resolution than 1 cm is required in practice. When using the microwave locating reflectometer the bandwidth B or rather the sweeptime T_S is technologically limited, so the actual output signal exists only during a limited time span window. It's correct analytical notation appears as follows

$$y(t) = \text{rect}\left(\frac{t}{T_S}\right) \cdot \sum_{i=1}^{M} r_i \cdot e^{j\omega_i \cdot t} \qquad (1)$$

and the Fourier transform $Y(j\omega)$ of the time windowed signal (1) can be written as

$$Y(j\omega) = T_S \cdot \sum_{i=1}^{M} r_i \cdot \text{si}\left(j(\omega - \omega_i)\frac{T_S}{2}\right) \quad . \qquad (2)$$

Due to the band limitation the reflections are disturbed by the si $= \sin(x)/x$-function. The base width of the si-function's main lobe is given as

$$\Delta\omega_W = 2\pi/T_S \quad \rightsquigarrow \Delta x_W = c/B \approx 7.5\,\text{cm} \quad . \qquad (3)$$

For the measurement system this means that discontinuities closer to each other than $\approx 7\,$cm can not be correctly resolved. If the magnitudes of their reflection coefficients differ, the resolution becomes even worse.

The Fourier transform can be used as a quick method to detect the existence of reflections but not the exact position. A pole extraction algorithm promises to improve the accuracy without increasing bandwidth. The sampled noisy output signal (N sample data length; $1/T_A$ sample frequency) can be written as

$$y(k) = \sum_{i=1}^{M} r_i \cdot z_i^k + n(k) \qquad \text{where} \quad z_i = e^{j2\pi \cdot f_i \cdot T_A} \quad .$$

The retrieval of poles z_i and residuals r_i allows for determining the locations and reflection coefficients of discontinuities in the tested device in the presence of noise $n(k)$. The 'Generalized Pencil of Function'-Method (GPOF-Method), also known as the 'Matrix Pencil'-Method [Hua89], [Mar91] yields a pole extraction algorithm which uses the solution to a generalized eigenvalue problem.

The GPOF algorithm computes the singular values σ_l of the $L * (N - L)$-matrix Y_1 which consists of values $y(k)$, where L is a parameter for which $M \leq L \leq N - M$ must hold. The number of poles M is normally unknown. A reasonable estimate $\hat{M}$ can be drawn from an analysis of the singular values σ_l, which show a descending order. A more or less significant gap between σ_M and σ_{M+1} exists and results in a local maximum of the singular value ratio $\eta_l = \sigma_l/\sigma_{l+1}$. Defining a sensitivity parameter η_G it is possible to estimate $\hat{M}$ from the condition $\eta_{\hat{M}} > \eta_G$

Due to noise it is often necessary to vary this sensitivity parameter. Choices too large or too small for η_G lead to underestimation $\hat{M} < M$ or overestimation $\hat{M} > M$, respectively. Typical values are $1.3 \leq \eta_G \leq 10$.

In order to demonstrate the improved resolution the density distribution inside the reactor has been simulated by a multilayer-structure (fig. 3), which consists of 3 layers. The dielectric constants $\epsilon_1 = 1.174$ and $\epsilon_2 = 1.272$ correspond to densities of $f_1 = 10.8\,$Vol% and $f_2 = 16.6\,$Vol% and they result in a reflection coefficient $r_0 = 0.02$.

Four multilayer-structures with different layer thicknesses Δx have been simulated with a signal to noise

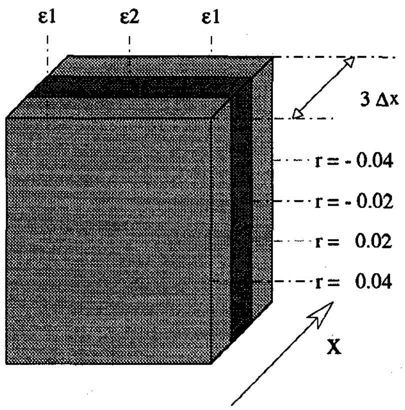

Fig. 3: Multilayer-structure as a modell for simulations

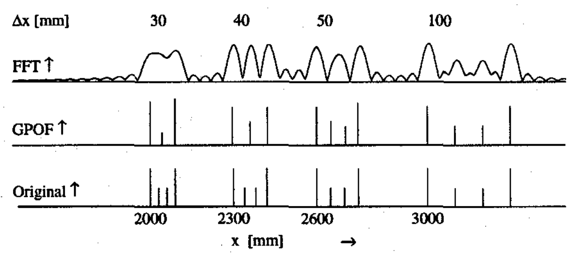

Fig. 4: GPOF-results for the multilayer-structure in comparison to original data and Fourier transform results

ratio of SNR = 40 dB, parameter $L = (N-1)/2 = 256$ and the sensitivity parameter $\eta_G = 1.4$.

In fig. 4 the comparison between GPOF-data and Fourier-transform results show clearly the improved resolution. The outer reflection planes are detected clearly for the different layer thicknesses. The inner boundaries between the layers can be detected very accurately up from $\Delta x = 50\,mm$. If the layers are too narrow, one central reflection is calculated for the two inner planes.

3 Measurement Results

An experimental setup consisting of a directional coupler filled with dielectric material and shorted at it's end (fig. 5) was used with the microwave locating reflectometer system for the verification of theory. The relative dielectric constant of the material filling the directional coupler and the semi-rigid line is $\epsilon_r = 2$, which

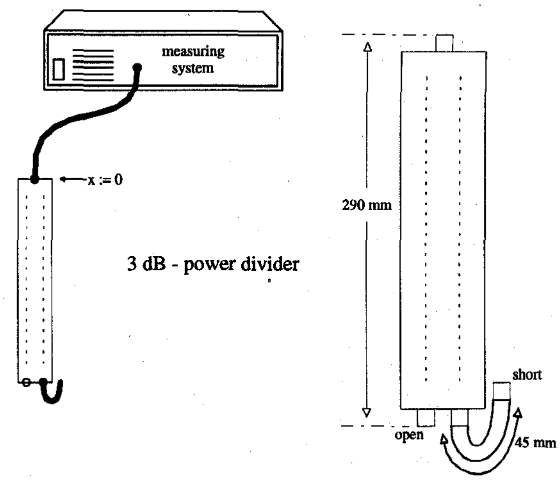

Fig. 5: Measurement setup with 3 dB-coupler and 45 mm semi-rigid line

results in electrical lengths of 410.1 mm and 63.6 mm. So the shortcut's electrical distance is 473.6 mm. The reference path was calibrated such that the coupler's input was located at $x_0 = 0 \Leftrightarrow t_0 = t_r$. The sampled mixer output signal was GPOF-analysed with a sample data length $N = 513$, parameter L was set to $L = (N-1)/2 = 256$. In fig. 6 it can be seen that

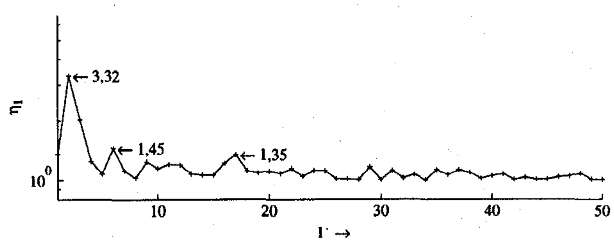

Fig. 6: Singular value ratio

a choice of $\eta_G = 3.0$ leads to $\hat{M} = 2$. The wave reflected at the shortcut travels a longer distance and passes through two additional SMA-connectors which accounts for a slightly smaller $|\hat{r}|$.

The choice of η_G determines the sensitivity of the GPOF method such that values $\eta_G = 1.4$ or $\eta_G = 1.3$ lead to pole number estimates of $\hat{M} = 6$ or $\hat{M} = 17$, respectively. To look at the balance between sensitivity and error rate, poles and residuals were calculated for

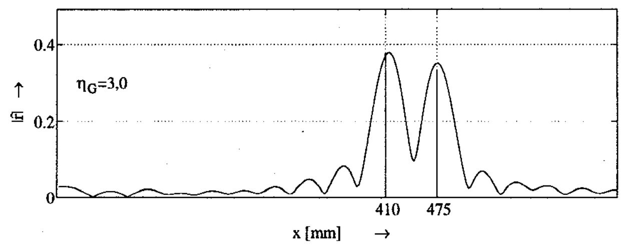

Fig. 7: Comparison of GPOF and FFT with $\eta_G = 3.0 \Rightarrow \hat{M} = 2$

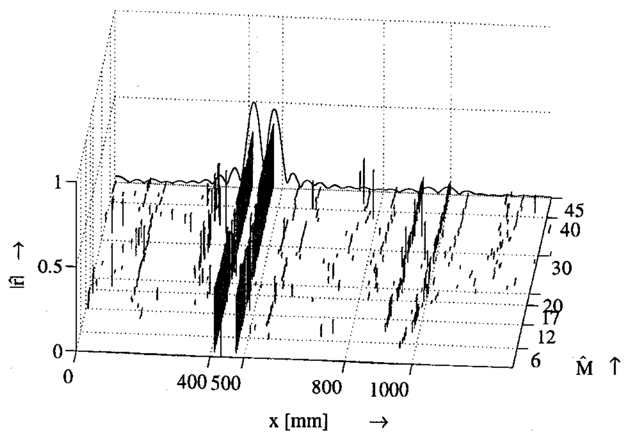

Fig. 8: GPOF-results for $\hat{M} = \{1 \ldots 45\}$

$\hat{M} = 1$ to $\hat{M} = 45$ [1] (fig. 8).

This kind of display reveals traces which allow for the distinction among systematic results and errors. Repeatedly calculated poles are taken to have a physical cause. In this particular case small primary reflections at the SMA-connectors and secondary reflections inside the coupler seem reasonable. It is also possible that the mixer produces harmonics of $\Delta\omega_i$. The criteria for a pole's significance are the $\hat{M}$-value of its first appearance and the continuity of its further appearances.

4 Conclusions

A microwave locating reflectometer has been presented as a new measurement tool to detect density variations in a fluid bed reactor in the short range. The application of the Generalized-Pencil-Of-Functions-Method makes it possible to improve the resolution capability of the measurement system using a given bandwidth of 4 GHz from a value of 7 cm to less than 1 cm. True reflections can be estimated correctly in the presence of noise. The improved resolution makes it possible to use the system for the planned application of measuring density profiles in fluidized bed reactors. Work on this topic is in progress.

[1] Note that due to noise some of the calculated poles were found in the lower z-plane and were ignored.

5 Acknowledgment

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