A Method for Impedance-Supported Reconstruction of Mixture Composition

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ABSTRACT

A new method is presented, which makes it possible to extend the application of the impendance methods to situations in which no information of the multiphase mixture is available. The method is not based on tomography, but works also with spatially distributed sensors, having the form of strips integrated in the wall in a non-intrusive way. These strips are acting as electrodes, producing various capacity fields which can be varied over the cross section of the channel within a very short time. The temporal signals of these strip-electrodes are composed into a multi-dimensional field of vectors.

By comparing the multi-dimensional vector field with a matrix of reference data a situation of optimum simularity can be evaluated and from this the flow pattern (bubbly-, annular-, spray-, stratified-flow,...) can be identified. Knowing the flow pattern, the evaluation of the signals can be continued for determining the local volumetric void fraction. The sensor and the method can be used as a universal fully automatisized instrument for measuring multi-phase flow in chemical engineering and in petrol engineering.

The method proved to be a very reliable technique and has been tested in a series of experiments. It was shown that it gives the local void fraction with an error less than 2 - 8 %, depending on the number of capacitive fields produced during a measuring cycle. If the measuring cycle can be extended to 1 s the error is down to 2 % and at shorter cycle periods - for example 0.1 s - the error goes up to 5 - 8 %.

Especially in horizontal flow - also with very wavy situations - the local void fraction can be measured with very good accuracy. With bubbly flow the variation of the bubble concentration over the cross section must be taken into account if very precise data are needed. Therefore, here a measuring cycle has to consist of a larger number of evaluated capacitive fields which means that the minimum measuring time is longer than the above mentioned 0.1 s.

But using not only the dielectric constant (capacitive method) as a sensoric signal but also the electric conductivity (impedance method) also mixtures of oil, gas and water - or in general multi-phase mixtures with gas and liquid components of different electrical properties - can be investigated.

1 IMPEDANCE METHOD

The impedance method is widely applied for measurement of volumetric concentrations in multi-phase flows. It is based on the different electrical properties (permittivity, conductivity) of the flow components and their effect on the measured impedance (capacitance, conductance) of an appropriate sensor. In non-conducting fluids, the capacitance of the sensor is measured; in conducting fluids conductance can be measured, either additionally or exclusivly. The majority of these applications comes from the field of two-phase flows, especially from capacitance measurement in non-conducting fluids. Popular applications employ parallel plate electrodes, Auracher [1]. The using of ring electrodes is described by Özgü et.al.[2], helical electrodes have been tested by Geraets et.al.[3], Abouelwafa et.al.[4]. A method of electrode excitation was proposed by Merilo et.al.[5] and incorporates the use of 6 strip-electrodes fed by a 3-phase voltage generator.

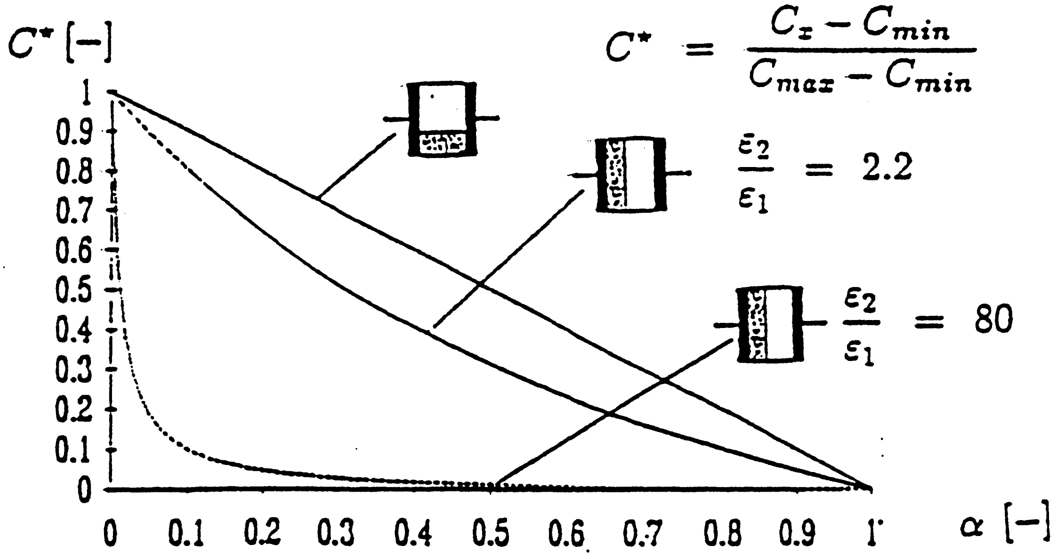

Figure 1: Dependence of the capacitance on the flow pattern

Although the impedance method offers a number of advantages like simultanous responce and no need for moving parts, its sensitivity to the flow pattern sometimes limits the range of application. The dependence of the impedance to the flow pattern, i.e. to the phase distribution within the sensing volume is illustrated in fig.1. It shows the capacitance of a parallel plate capacitor filled with two dielectrics of permittivities ε_1, ε_2, calculated for the component interface perpenticular (case I) or parallel to the electrodes (case II)[6]. The normalized capacitance C^*

$$C^* = \frac{C_{meas} - C_{min}}{C_{max} - C_{min}} \tag{1}$$

in case I is calculated by parallel connection of the 2 particular capacitances C_1, C_2, in case II however, by their serial connection.

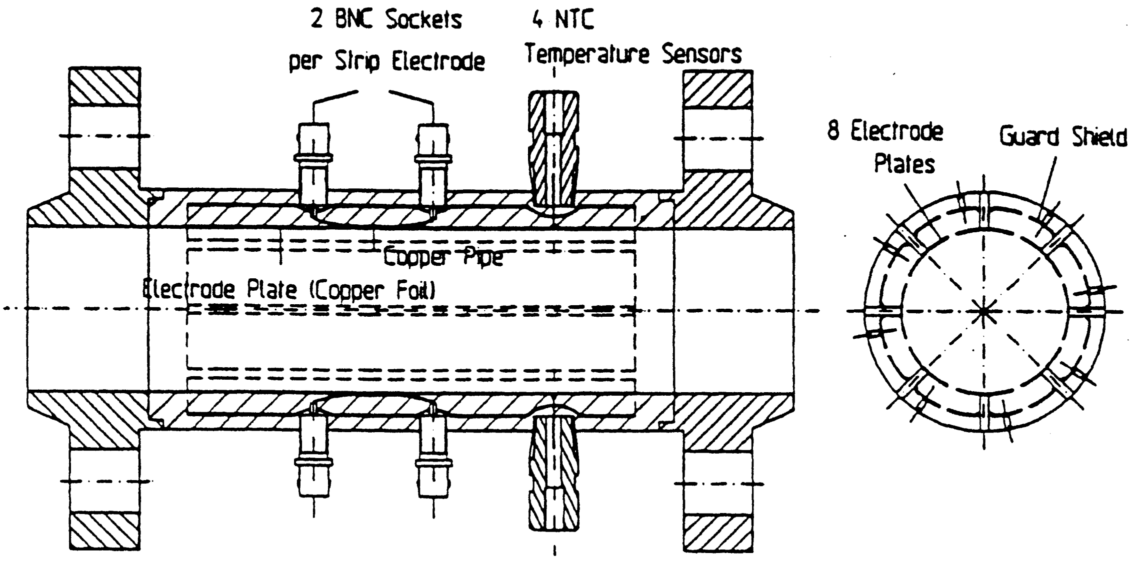

Figure 2: Non-intrusive probe (Ø54mm, L = 300 mm) with 8 plate electrodes

As Fig.1 clearly shows, the difference between the total capacitance $C^*(\alpha)$ for these two cases depends on the permittivity ratio $\varepsilon_1/\varepsilon_2$ of the flow components (α denotes the volume fraction of component 1). In gas-water flows, where $\varepsilon_1/\varepsilon_2 \approx 80$, the two curves differ so much, that the determination of the void fraction α by capacitance measurement, without any information about occuring flow pattern is connected with uncertainties far too high, and therefore becomes unreasonable. For the generally occuring flow conditions, especially with dispersed flow components a number of analytical models [7] - [10] are known for calculation of the permittivity ε of a mixture of two fluids of particular permittivities $\varepsilon_1, \varepsilon_2$. The course of C^* for these flow mixtures lies always between the two cases shown above [6]. Summarizing it can be said, that the sensitity of the impedance method to the distribution pattern of the components leads to different characteristics for every flow regime. In flow situations, where this curves differ too much, more information about the flow is needed.

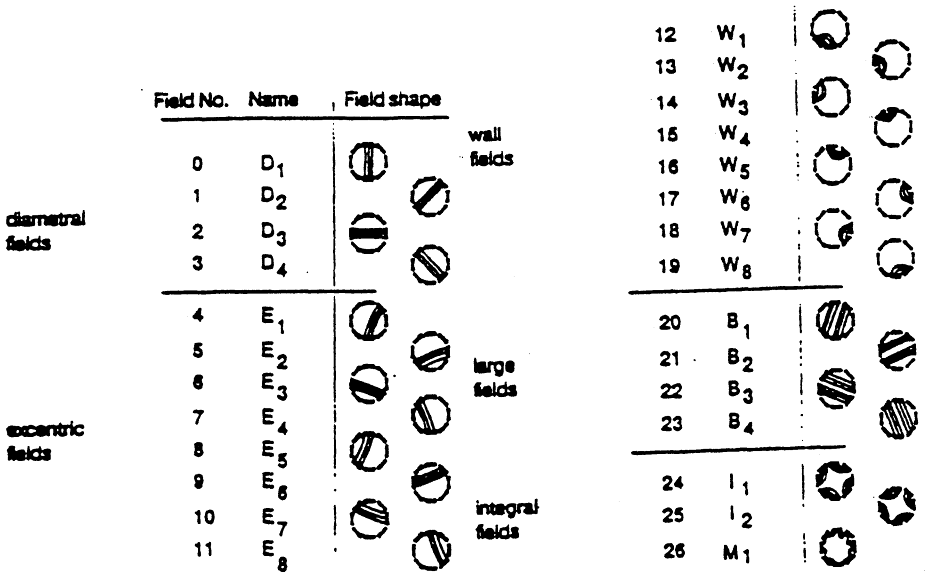

Figure 3: Measuring fields used with the impedance probe

To overcome the insufficiences mentioned above, a new approach is made for concentration measurement in multi-phase flows [10]. Although the proposed method has been originally developed with respect to offshore applications in oil-water-gas mixtures, it can be easily applied to a much wider field of multi-component flows. The main part of the described measuring technique is a non-intrusive impedance probe consisting of eight plate electrodes mounted near the surface of the inner side of the tube made of glass-fiber reinforced plastics. To reduce influences from outside the sensor a guard shield was also included. The influence of the temperature is captured by 4 circumferentially distributed NTC temperature sensors, directly mounted on the electrode plates (see fig.2).

With this probe, the impedance between different combinations of electrodes – the so-called measuring fields – is measured. For every measuring field, the impedance – as an intregral parameter – is determined by the component distribution within the whole sensing volume of the probe. However the individual domains of the sensing volume make different contributions to the total amount of the flow-influenced probe impedance. Therefore characteristic distribution patterns for the spacial sensitivity [11] can be observed, which allows one to classify the multitude of measuring fields into several groups.

Each group consists of a certain number of fields, which depends upon the degree of field symmetry, the fields being "rotated" against each other by an angle $\Delta\psi = k \cdot 360°/8$. These are the diametral fields $D_1 - D_4$, eccentric fields $E_1 - E_8$, wall fields $W_1 - W_8$, large fields $B_1 - B_4$, intregral fields I_1, I_2 and the Maltese-cross shaped field M_1 see fig.3. Although a much higher number of fields is theoretically possible the conducted tests proved, that the 27 fields shown above are sufficient to ensure a good and unambiguous performance over the flow regimes of practical relevance.

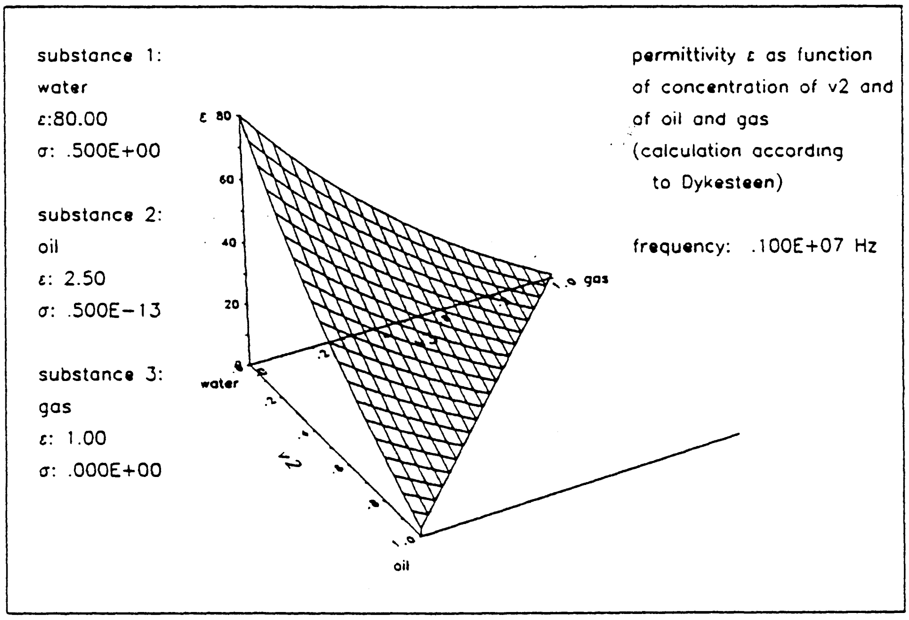

Figure 4: Calculated permittivity of a water-oil-gas mixture at 1 Mhz measurement frequency

Within each measurement cycle, the probe impedance for m fields is recorded. This measurement vector V, consisting of m impedance readings, is compared to a stored reference matrix M of dimension m × n. M consists of the $(m \cdot n)$ impedance values representing n different flow compositions over several flow regimes. Within every flowregime, the component concentration is increased gradually, the stepwidth depending on the overall accuracy of the measurement setup (typ. 2%). In this way the column numbers contain the encoded information about the flow regime and the flow composition.

It proved useful to generate both V and M with normalized, relative impedance values, $0 \leq Z_{ij} \leq 1$ as described in equation (1). This ensures good comparability and achieves independance of the actual probe dimensions. In the next step V and M are compared, calculating the error

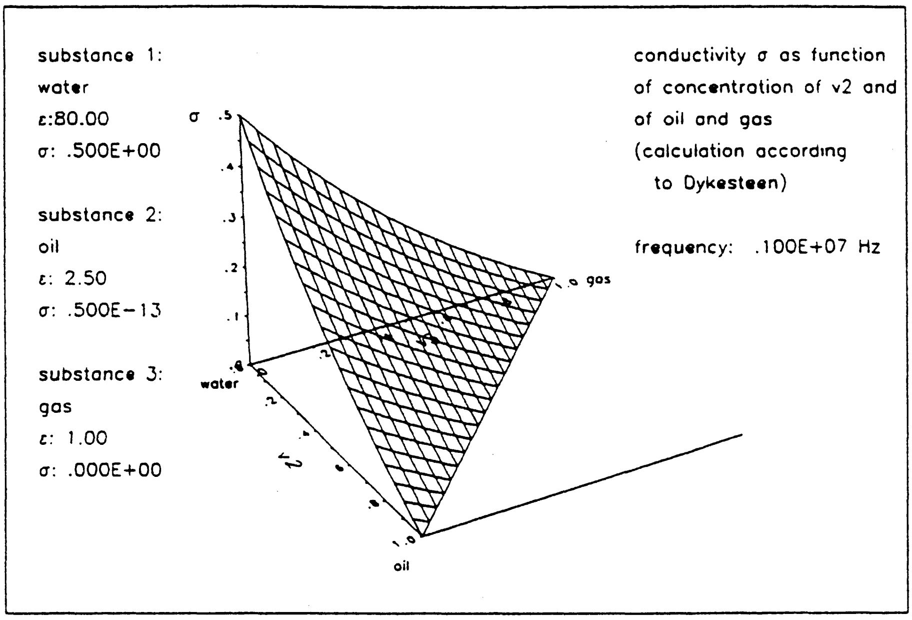

Figure 5: Calculated conductivity of a water-oil-gas mixture at 1 Mhz measurement frequency

$$s(j) = \sum_{i=1}^{m} (|V_i - M_{ij}|)^{1/2} \tag{2}$$

for every column of M. Due to the use of dimensionless impedances which lead to small error values in the range $s(j) < 1$ over most interesting flow regimes, eq. (2) shows a sharper detection of the minimum, compared to the sum over error squares, often used fore this purpose. The reconstruction is finally performed by determining the best-fit column ($s(j_0) = min\{s(j)\}$). The flow composition and the occuring flow regime are then determined by decoding the address of the determined column j_0.

2. 3-PHASE MEASUREMENT

To determine the void fraction of a three phase flow, i.e. oil, water and gas, two independend electrical informations are needed. Following Dykesteen [10] the complete usage of the measured impedance, consisting of capacity and conductivity, is enough. Fig. 4 shows the calculated capacity shape of a three-component mixture of water ($\varepsilon \approx 80$), oil ($\varepsilon \approx 2$) and gas ($\varepsilon \approx 1$). Figure 5 shows the calculated specific conductivity shape of a three-component mixture of water ($\sigma \approx 0.5$), oil ($\sigma \approx 0.5$ E-13) and gas ($\sigma \approx 0$). It has been shown, that the shapes of the two parts of the impedance are different enough to detect the void fractions

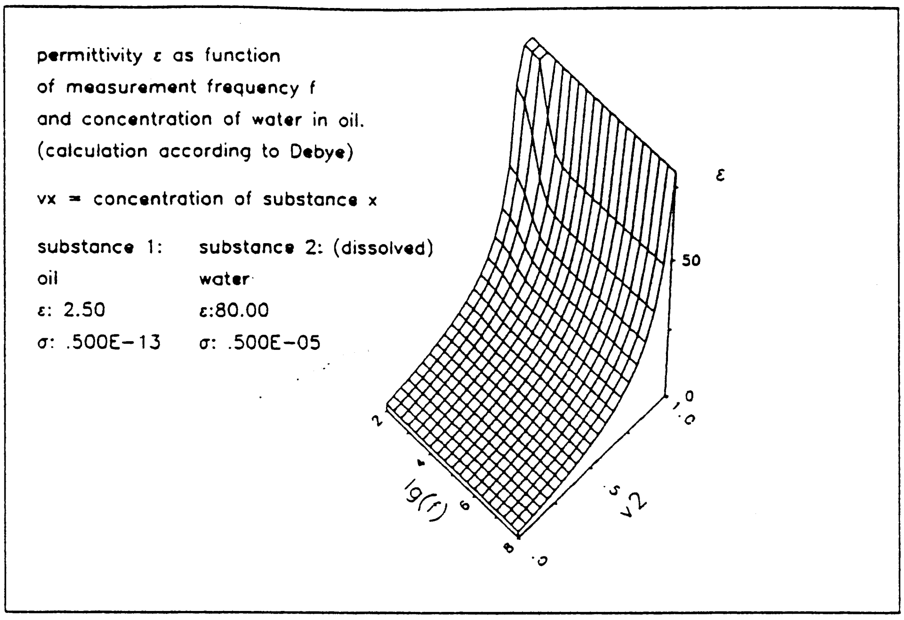

Figure 6: Calculated conductivity of a water-oil mixture with changing measurement frequency from 100 Hz to 100 MHz

α for gas and β for water. The measurement of the capacity gives a line of concentration ratios and the measurement of the conductivitiy gives another line of different concentration ratios, which meat at the actual mixture concentration. By using the HP impedance meter both values are simultaneously captured.

If there occur additional influences – like the flow pattern as mentioned above – a third information about the water-oil ratio will be available by changing the measurement frequency, because there is a change in conductivity of the water according to the frequency, but no change for oil and gas (see Fig.6). This will be very important for situations where no information for sure is available about the carrier phase of the oil-water mixture.

3. GENERATION OF THE REFERENCE MATRIX

The reference matrix can be generated in different ways: by numerical calculation or by calibration.

3.1 Numerical Calculation

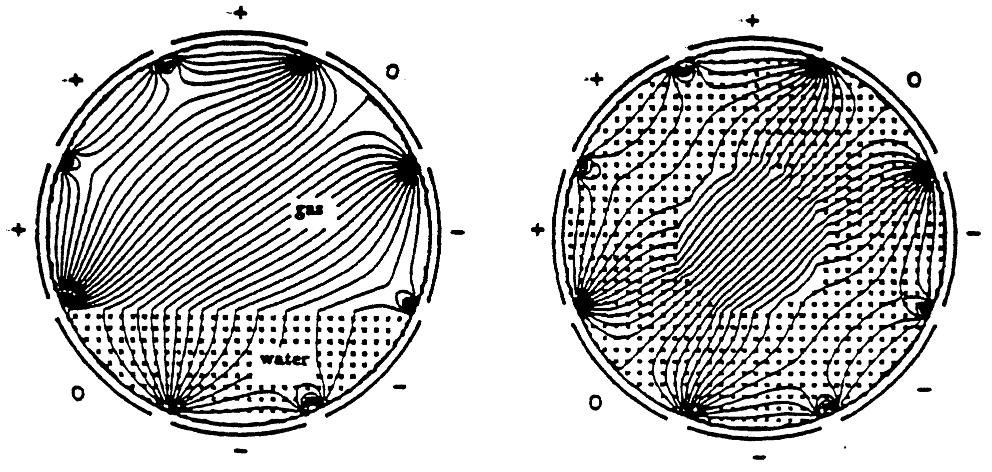

Figure 7: Equipotential lines in the probe for stratified (left side) and annular two-phase flow of water and air

The numerical method [10], [12] is based on the solution of Poisson's equation for a domain of permittivity ε and a space-charge density ϱ:

$$\nabla^2\varphi = \Delta\varphi = -\frac{\varrho}{\varepsilon} \tag{3}$$

In the special case, with no free charges ϱ equation (3) becomes

$$\Delta\varphi = 0 \tag{4}$$

Δ represents the Laplace operator and φ describes the potential. In cartesian coordinates, and if one of the three dimensions can be regarded infinitive, equation (4) simplifies to

$$\frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial y^2} = 0 \tag{5}$$

The calculation of the 3-dimensional field can be accomplished by the use of a finite-difference method [13]. The Capacitance C_{AB} between any two of a given set of electrodes is determined by the existing electrical field between the assembly, i.e. by the potential distribution between the electrodes. In this way the impedances between any electrodes can be calculated for every specific flow

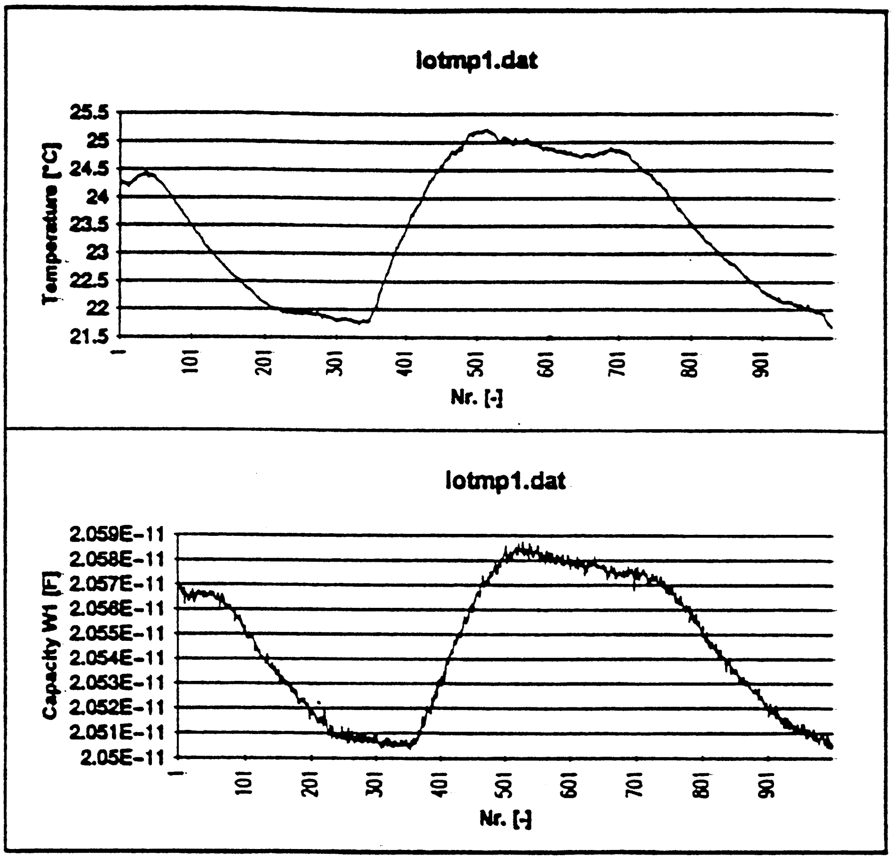

Figure 8: Temperature dependence of a wall field during a time cycle of 36 hours in an isolated room

distribution within the probe so that the distribution of the impedances for every measuring field is obtained. Fig. 7 shows calculated equipotential lines for stratified and annular two-phase flow of water and air.

The problem of any numerical method is to include effects of the set-up like coated electrodes or the shape of the electrodes which causes movements of the charges inside the electrodes not described by the simple theory. Due to this the calculation of the impedance has to be added to calibrations with the real probe.

3.2 Calibration

A very important part of the calibration is the determination of the minimum impedance Z_{min} of the probe correspondig to the filling with a gas only. This minimum impedance depends strongly on the design of the probe, i.e. the thickness of the coating of electrodes and its uniformity. The distance of the

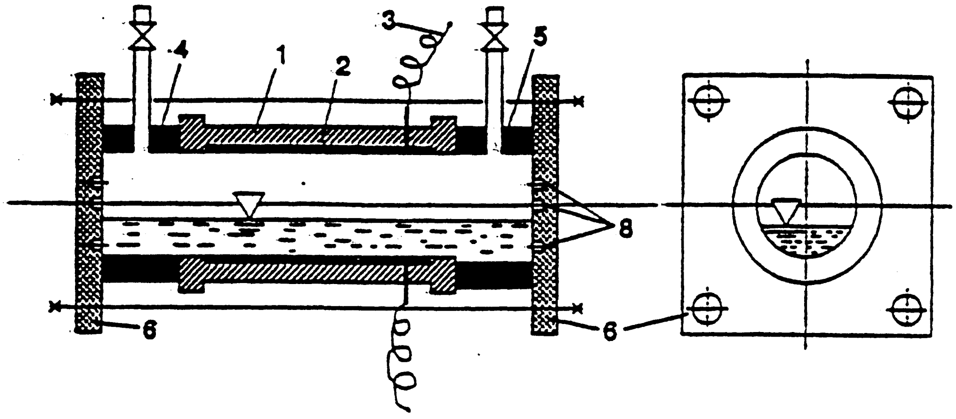

Figure 9: Apparatus for stationary calibration. Impedance probe (1), electrodes (2), electrical connections (3), tubes (4),(5), plexyglass planes (6), positioning bores for phantomes (8)

plate electrodes is the mean factor for the sensitivity of the wall fields. On the other hand environment influences like temperature or adsorption of humidity by the sensor plastics can change the minimum impedance by a multiple of the difference of (Z_{max} - Z_{min}). All these influences must be measured or – if this it not possible – avoided. Fig.8 shows the temperature dependence of a wall field. The change of capacity caused by 3 degrees C represents about 10 % of the measurement range.

In the second step the reference matrix is generated. This can be done under two conditions:

- real flow conditions
- stationary conditions

In the first case, the impedance probe is exposed to a multi-phase flow of the required regime and flow components. During a stepwise alteration of the flow composition the impedance values for all measuring fields are captured. For this calibration procedure, a multi-phase measurement technique is required as reference for the actual volumetric flow composition. In this case quick closing valves has been used for stationary flow and a 5Ci γ-ray densitometer for stationary and instationary flow. In flow regimes with fluctuating component concentrations, e.g. slug flow, it has to be ensured, that representative values of the void fraction are recorded. If the reference matrix is generated by calibration in real flows, the flow itself can be regarded as a "black box", and no further assumptions concerning the phase distribution are required. By consequence even exotic flows can be covered. The maximum possible reconstruction accuracy is determined by the accuracy of the reference measurement used for calibration.

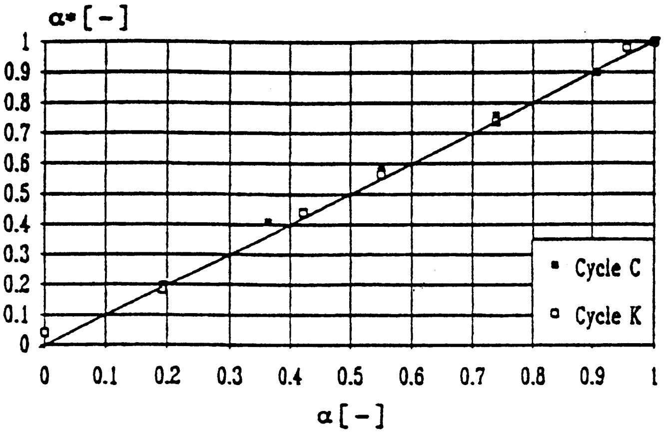

Figure 10: calculated void fraction α^* versus reference void fraction α for stratified flow of oil and gas comparing the complete cycle K (27 fields) and the short cycle C (8 fields)

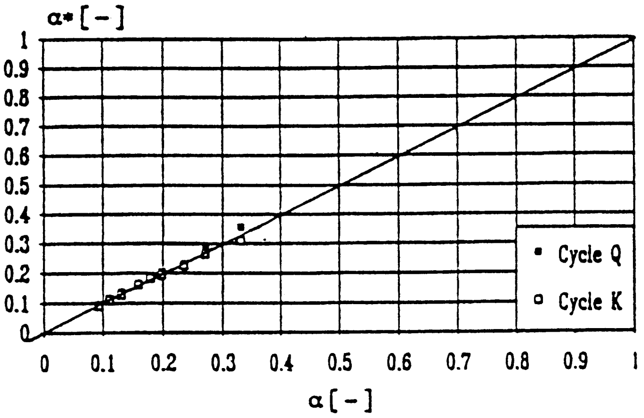

Figure 11: calculated void fraction α^* versus reference void fraction α for bubbly flow of water and gas comparing the complete cycle K (27 fields) and the short cycle Q (4 fields)

If multi-phase test facilities are not available, a modified calibration procedure, the stationary calibration can be used instead. In this case the component distribution is simulated by phantoms. The phantoms could be either geometricly exact designed parts like acrylic pipes or sticks representing, e.g. annular flow, or averaging parts like plastic foams representing bubbly flow. Though the density distribution of the exactly defined parts is well known, the distribution of the foams has to be measured by a reference technique also. This is done by the simultanous measurement of a γ-ray densitometer and the impendance meter of the probe filled with the foam.

The third stationary calibration method is the stepwise decrease of the void fraction by injecting equal amounts of liquid by the help of a syringe while flanging the probe between two planes of plexiglass (see Fig.9). This kind of calibration has to be repeated for several inclinations of the probe corresponding to flow pattern changing from stratified flow to slug or plug flow.

It is essential, that the void fraction steps $\Delta\alpha$ between adjacent impedance vectors stored in the reference matrix remain under a certain magnitude, which is determined by the overall accuracy of the impedance measurement (typically $\Delta\alpha = 2\%$). This is achieved by interpolation algorhithms applied to the data obtained.

4. EXPERIMENTAL DATA

The experimental data shown below have been obtained with an impedance probe in the stratified, bubbly and annular flow regime. The measurements were carried out in oil-gas and water-gas flows of ambient pressure with tap water, SHELL Ondina 15 oil and air. The multi-phase test loop was equipped with horizontal and vertical test sections of 10 m length. Liquid flow rates could be adjusted in the range of $0.3 \leq \dot{V}_l \leq 4l/s$, gas flow rates were between $0 \leq \dot{V}_g \leq 9l/s$. Thus a void fraction of $0 \leq \alpha \leq 0.88$ could be covered. The reconstruction was based on capacitance measurement at a frequency 100 kHz, using a HP 4284A impedance meter. This allowed for a measurement time $t_{meas} \approx 30ms$ per field at a basic accuracy in the range of 0.1%.

According to the description of the reconstruction technique given above, it is to be expected, that the best results are obtained, if cycles with a large number of measuring fields are employed. However this is connected with a long measuring time (up to 1.8s) per cycle. Under many practical conditions, this is not tolerable, especially if in the time history of the void fraction fluctuations have to be tracked.

In order to increase the measurement rate per cycle some short cycles had been composed of few fields, containing a maximum of information corresponding to a special flow pattern (for detailed information see [6], [12]). The short cycles had been cheked for three flow patterns: for stratified flow (Fig.10), for bubbly flow (Fig.11) and for annular flow.

While keeping the inaccuracy of the reconstruction below 10% the measurement speed could be accelarated by factors of 4 to 8. This causes a measurement strategy of two steps. In the first step a complete cycle is used to determine the flow pattern and the void fraction. With the information about the flow pattern a shorter cycle is used for a faster detection of the void fraction.

5. DISCUSSION AND CONCLUSIONS

The results presented in this paper demonstrate the excellent performance of the new developed, impedance-based reconstruction technique for multi-phase flows. This improved technique avoids the disadvantages of the conventional impedance method by multi-channel measurement with the help of numerous fields and a non-intrusive, multi-electrode probe. All the calculation steps and control functions for the impedance meter are easily performed by a regular size PC. The method detects the occouring flow regime and the volumetric flow composition. Its application range can also easily be extended to three-phase flows.

The required reference matrix can be generated by calibration or numerical calculation or a combination of both. The best results are obtained by a combination of stationary calibration of the sensor itself and the calibration for the void fraction in a real two-phase flow. To speed up the measurement rate a sophisticated combination of measurement fields is created using preinformation about the flow pattern.

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Symbols

C	[F]	capacitance
C^*	[-]	relative capacitance
L	[m]	length of probe
M		Matrix
Q	[As]	charge
s	[-]	error value
V		vector
$\dot{V}$	$[m^3/s^{-1}]$	flow rate
w	[m/s]	velocity
x, y		cartesian coordinates
Z	$[\Omega]$	impedance
Ø	[m]	diameter of probe
α	[-]	volumetric viod fraction
ε	[-]	permittivity
ϱ	$[Asm^{-3}]$	space-charge density
σ	$[\Omega^{-1}m^{-1}]$	specific conductivity
φ	[V]	potential
ψ	[-]	angle

Indices

g	gas
i	row
i	row
j	column
l	liquid
s	superficial