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Signal response of wire-mesh sensors to an idealized bubbly flow

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ABSTRACT

Wire-mesh sensors are widely used to characterize gas-liquid two-phase flows and single-phase mixing processes. The geometry of the electrode grids and the way of the signal readout generates a three-dimensional electrical field in the vicinity of the electrode wires. Resulting electrical currents at the receiver electrodes, representing the primary measuring information, are calculated by a three-dimensional potential field simulation within the sensitive volume formed by the electrode wires, whereas bubbles are taken into account as simplified, spherical or elliptical objects placed at different locations in the calculation domain. The response of the sensor to the passage of such synthetic bubbles is studied. A significant deviation from the linear dependency between the received current and the local instantaneous gas fraction is found. Overshoots of the current above the reference value obtained by calibration in plain liquid occur. Furthermore, the response of the sensor depends on the axial distance between the transmitter and the receiver electrode grids. Swarms of bubbles of small size passing through the grids of the wire-mesh sensor lead to an average decrease of the current which can be described by the average conductivity of an emulsion according to Maxwell.

1. Introduction

Wire-mesh sensors are widely used to characterize gas-liquid two-phase flows and single-phase mixing processes. The first concept was patented by Johnson (1987), who proposed it for a measurement of the holdup of an electrically conducting phase in a mixture of two fluids. The measurement of two-dimensional hold-up profiles was achieved for the first time by the group of Mewes (Reinecke et al., 1996) by applying tomographic reconstruction techniques. A signal acquisition method allowing a high spatial and temporal resolution without the need of a tomographic reconstruction was introduced by Prasser et al. (1998) and is currently in use in numerous laboratories worldwide.

The primary measuring signal of the wire-mesh sensor is a two-dimensional distribution of measuring values that are proportional to the conductance G sampled at each crossing point of transmitter and receiver wires. A cell constant γ resulting from the geometry of the electrodes connects conductance G with the conductivity of the fluid σ.[1] Individual values are obtained for each crossing point of a transmitter and a receiver wire. If the sensor is used for holdup measurements, these primary readings have to be converted into local instantaneous volume fractions, e.g. of the non-conducting gaseous phase (void fraction measurement). In the past, a linear relationship was applied, i.e. it was assumed that the conductivity of the two-phase mixture residing in the control volume defined by the crossing electrode wires is a linear superposition of the conductivities of both phases, weighted by the volumetric fractions. In case only one of the phases is conducting, the signal is proportional to the holdup of this phase. The local instantaneous volumetric gas fraction can then be found by relating the conductance measured at a crossing point to the calibration value:

$$\varepsilon_{i,j,k} = 1 - \frac{G_{i,j,k}}{G_{cal,i,j}} = 1 - g_{i,j,k} \tag{1}$$

It was believed that this linear relationship is a reasonable approximation for those cases, in which the characteristic scale of the interface between the conducting and the non-conducting phases (e.g. the bubble size) is much larger than the resolution given by the sensor mesh. If this is the case, then most of the local instantaneous void fraction values collected by the sensor are either zero or unity. The linear assumption was based on the view that intermediate values, which are affected by the uncertainty of a model used to describe the conductivity of the two-phase mixture do not have a large weight in secondary measuring quantities, like average void fractions or bubble sizes. The applicability of the lin-

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[1] Conductivity σ [S/m] is conductance G [S = A/V = 1/Ω] times a cell constant γ [1/m], the conductance G is recorded electrical current I [A] divided by the transmitter voltage U_{trans} [V]. Often only normalized quantities are interesting, e.g. the conductance normalized to a calibration value obtained in a plain conducting liquid

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Nomenclature

Symbol	Designation, Unit
D	diameter, m
d	relative diameter, –
G	conductance, S, A/V
g	normalized conductance, –
I	electrical current, A
p	relative pitch, relative distance between centers of adjacent bubbles, –
s	systematic error of bubble diameters obtained from simulated WMS signals, %
U	voltage, V
v	dimensionless bubble volume, –
w_0	superficial velocity, m/s
x	axis, in the direction of the propagation of the bubbles, m
y	axis, parallel to the receiver wires, m
z	axis, parallel to the transmitter wires, m
γ	cell constant, 1/m
Δ	distance, m
δ	relative distance, –
ε	volumetric gas fraction, void fraction, –
σ	conductivity of the fluid, S/m
ax	axial, in the direction of the propagation of the bubble
bub	bubble
c	conducting phase
el	electrode wire
g	gas
l	liquid
lat	lateral, between neighboring electrode wires
i	index, number of the transmitter electrode
j	index, number of the receiver electrode
k	index, number of the sample in a sequence of measurements
sw	swarm of bubbles

ear relationship was confirmed, for example, by comparison with fast X-ray tomography (Prasser et al., 2005). The statements in this paper hold of course only within the limits of the tested set of superficial velocities (air 0.02–0.40 m/s, water 0.0–0.69 m/s) belonging to the bubbly and the slug flow regimes. And a closer look to the agreement between wire-mesh sensor and X-ray tomography reveals bands of deviation of $\overline{\varepsilon_{X\text{-}ray}} - 0.04 < \overline{\varepsilon_{wms}} < \overline{\varepsilon_{X\text{-}ray}} + 0.02$ (see Fig. 16 in Prasser et al., 2005). Such absolute uncertainties can become quite unacceptable in bubbly flows at small superficial gas velocities.

In the same direction point the results of some measurements in the bubbly flow regime in a vertical upwards flow in a pipe of 200 mm diameter at the TOPFLOW facility of Rossendorf, which resulted in unrealistic cross-section averaged gas fractions. For small superficial gas velocities, the gas holdup was too high to be explained by a positive drift velocity, which should always be in present in a vertical flow (Beyer et al., 2008). The same authors found systematic deviations between superficial gas velocities calculated from the injected gas flow rate and those reconstructed from velocity and void fraction profiles obtained from a pair of mesh sensors (see Beyer et al., 2008, as well).

Effects of the intrusiveness of the sensor were found by observing the passage of bubbles through the sensor grids with cameras. The split of bubbles into fragments was reported already by Prasser et al. (2001). Wangjiraniran et al. (2003) investigated the change of the bubble velocity caused by a WMS in a bubbly flow with low superficial liquid velocities, $w_{0,l}$ = 0.1 and 0.2 m/s. The authors used the digital processing of image sequences from a high speed video camera and found that the bubbles are decelerated by about 40%–50% compared to the bubble velocity upstream of the sensor. In addition, Fuangworawong et al. (2007) studied the intrusive effects in a counter-current bubbly flow, and a similar bubble deceleration has been observed. Ito et al. (2011) continued the research in this line and found that the decelerating effect vanishes at higher superficial liquid velocities. It turns into a slight acceleration, which is proportional to the obstruction of the flow cross-section by the thickness of the sensor electrodes.

Other strange observations were made in the raw signals. The cell constant of each crossing point is found in a calibration with the measuring cross-section filled completely with a plain electrically conducting fluid (or the more conducting one, in case of aiming at a measurement with two fluids of different conductivity). During the presence of the two-phase flow, one would expected instantaneous conductance values that always stay below or equal this calibration value. In reality, overshoots are observed regularly. Since the local conductivity of the two-phase flow must be below the calibration value, the problem can only be explained by changes of the cell constant. In fact, during calibration, the electrical potential field develops in an undisturbed geometry of a uniformly conducting continuum. In case of an equal pitch between electrode wires, there are clear symmetry lines dividing the measuring plane into cells of equal size (at least far from side walls), and the corresponding cell constants are equal. If a gas-liquid interface is present, this symmetry may be broken and the cell constants become non-uniformly distributed, i.e. one cell may get a bigger value, while the neighbor gets less.

The third question concerns the applicability of a simple linear relationship between holdup and conductance signal in a finely dispersed bubbly flows. When the bubbles are much smaller than the lateral pitch of the wires in the grids of the sensor, then the bubbles are no more resolved as individual objects. It has instead to be expected that the sensor acquires a conductance signal, which is rather given by the average conductivity of an emulsion. The dependency between conductivity and holdup for a finely dispersed mixture of fluids with different conductivities is depending from the holdup in a rather nonlinear way, as, for example, described by the equation of Maxwell:

$$\sigma = \sigma_c \frac{1-\varepsilon}{1+\frac{\varepsilon}{2}} \tag{2}$$

In general, also in case of large bubbles, it might be questioned if the usually applied linear relationship between conductance and volumetric gas fraction is the best approximation to obtain local instantaneous gas fraction values in cells not completely covered by the internal of the bubble. Also here, it has to be posed to a test, if Maxwell's equation can yield better results.

To summarize, in the present paper, the following four questions will be discussed:

1. What is the reason of overshoots of the local instantaneous conductance signals above the corresponding calibration values?
2. How should these overshoots be treated during the transformation of primary measuring information into volumetric gas fractions or bubble sizes?
3. Is the linear relationship between conductance and volumetric gas fraction correct, or is it better to apply Maxwell's equation for the conductivity of a two-phase mixture?

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