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CAPACITANCE WIRE-MESH SENSOR APPLIED FOR THE VISUALIZATION OF THREE-PHASE LIQUID–GAS–SOLID FLOW

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Abstract. *Wire-mesh sensors have been widely applied to investigate gas-liquid flows in past where measured resistance or capacitance distributions over sensor crossing points are converted into gas or liquid holdup distributions. In this work we report on the application of the wire-mesh sensor for the measurement of cross-sectional solid concentrations in solid-gas-liquid flow. As the electric permittivity of solid particles are different from those of gas, water or oil, measuring this property can be used as an indication of solids distribution. The results indicate that the wire-mesh technique can be applied as a tool for the fluid dynamic study of three-phase liquid–gas–solid systems.*

Keywords: *three-phase flow, solid–gas–liquid flow, wire-mesh sensor.*

1. INTRODUCTION

Liquid–solid particles (slurries) are widely encountered in chemical, mineral, and petroleum industries among many others which is widely found in various operations, for instance, dissolution, crystallization, adsorption, polymerization, transport and so on (Paul *et al*., 2004; Soo, 1967; Schramm 2005). In oil and gas production industry, sand production is one of the main problems faced. Producing sand in the hydrocarbon flow can cause serious problems to the production facilities. It can lead to equipment damage, inefficient separation, flow line plugging, production shutdown, economic losses also cause safety and environmental concerns. Furthermore, producing even relatively low amounts of sand can result in erosion of the pipeline when the velocities are high due to the impact of solid particles transported within a fluid. Thus, monitoring the solid phase distribution of such flows is of increasing industrial and scientific interest. The monitoring and visualization of solid concentration distributions inside pipes or vessels is therefore of great interest, once the knowledge of the spatial solids fraction distribution is important for predicting the performance of various processes.

2. WIRE-MESH SENSOR

Wire-mesh sensors are imaging instruments that have been used widely for gas–liquid and liquid–liquid two-phase flow measurements. It provides flow images at high spatial and temporal resolutions and it has been applied by many researchers for multiphase flow imaging. The sensor consists of two electrode planes spanned in the cross section of the pipe. Each plane of parallel stainless steel wires (transmitter and receiver) has an angle of 90° to each other and are separated by a small axial distance, forming a grid of electrodes. The associated electronics measures an electrical property (resistance or capacitance) of the flowing media in the gaps of all crossing points at high repetition rate. Based on raw data and knowing the electrical properties of substances involved, is possible to determine instantaneous phase distribution of a two-phase mixture over the cross-section (Prasser *et al*., 1998). Recently the capacitive wire-mesh sensor was used to investigate cross-sectional solid concentrations in solid–liquid mixtures (Dos Santos *et al*., 2016) for the first time to visualize and measure the solids distribution in a stirred reactor.

The capacitance wire-mesh sensor utilizes an appropriate AC excitation and measuring scheme. Hence, a sinusoidal alternating voltage is applied for excitation and the receiver circuit must encompass a demodulation scheme. The amplitude of measured AC voltage is proportional to the relative permittivity ε_m of the fluid surrounding a crossing point according to Da Silva *et al*. (2007).

$$V = a \cdot \ln(\varepsilon_m) + b \tag{1}$$

where V is the sinusoidal alternating voltage V demodulated by a logarithmic detector and a and b are constants (for each single point) related to the characteristics of electronic circuits employed. In order to convert the measured voltages to relative permittivity values and further obtain the phase fraction distributions, a calibration routine is necessary where two know reference values are needed. Two calibration measurements are acquired: one for the empty cross section $\varepsilon_{air} = 1$ (low reference value V^L) and one for the filled cross-section completely flooded with liquid, e.g. $\varepsilon_{water} = 1$ (high reference value V^H).

$$V^{\mathrm{L}}(i,j) = \frac{1}{N}\sum_{k=0}^{N} V(i,j,k), \tag{2}$$

$$V^{\mathrm{H}}(i,j) = \frac{1}{N}\sum_{k=0}^{N} V(i,j,k). \tag{3}$$

which is an average of the raw data over a sufficient temporal range. Here, i and j denote the wire indices, k the temporal sampling point index and N the number of measured frames. Using air as lower permittivity reference substance and liquid water for high reference, the relativity permittivity can be obtained as

$$\varepsilon(i,j,k) = \exp\left(\frac{V(i,j,k) - V^{\mathrm{L}}}{V^{\mathrm{H}} - V^{\mathrm{L}}}\ln(\varepsilon_{\mathrm{water}})\right) \tag{4}$$

V^H and V^L are respectively the values of water and air from the calibration measurements (eq. 2 and eq. 3).

As mentioned formerly, Dos Santos *et al*. (2016) performed experiments to investigate solid concentrations in solid–liquid mixtures and a linear relationship between the measured permittivity and the phase fraction was found. In order to determine the local solid fraction distribution α only three references are required: (1) section filled with water, (2) empty (air reference) and (3) a known mixture (wet-sand reference). References (1) and (2) are used to convert raw data into relative permittivity and then (1) and (3) to convert relative permittivity into sand fraction.

$$\alpha(i,j,k) = \left(\frac{\varepsilon_{\mathrm{m}}(i,j,k) - \varepsilon_{\mathrm{water}}}{\varepsilon_{\text{wet-sand}} - \varepsilon_{\mathrm{water}}}\right) . \alpha_{\text{wet-sand}} \tag{5}$$

where $\alpha_{\text{wet-sand}}$ is the maximum solid fraction in a liquid-solid mixture. This value can be obtained by knowing a certain amount of liquid inserted in a recipient. The volume of water remaining above the sand surface is measured. Thus, the residual water fraction can also be measured resulting maximum solid fraction.

$$\alpha_{\text{wet-sand}} = (1 - \alpha_{\text{residual-water}}) \tag{6}$$

3. RESULTS

With the purpose validating the system capability to measure solid distributions, an experiment was performed using the wire-mesh sensor attached to a pipe segment (100 mm pipe segment long and 50.8 mm internal diameter) filled with water (conductivity 92 μS/m), silica sand with a density of 3650 kg/m³, loose pack bulk density of 1.68 g/cm³ (100 lbs./ft³) and grain sizes of 40/70 US Mesh/Grid (0.42 mm – 0.21 mm) and 140/270 (0.105 mm – 0.053 mm) and air, the latter in order to facilitate the agitation process (simulation of dynamic flow). Figure 1 depicts the pipe segment containing the wire-mesh sensor with 16 emitters and 16 receiver electrodes was placed in a horizontal position in order to separate the substances and measurements were acquired. Table 1 shows the result images for six different set-ups where the three phases can be clearly recognized by the permittivity colour scale.

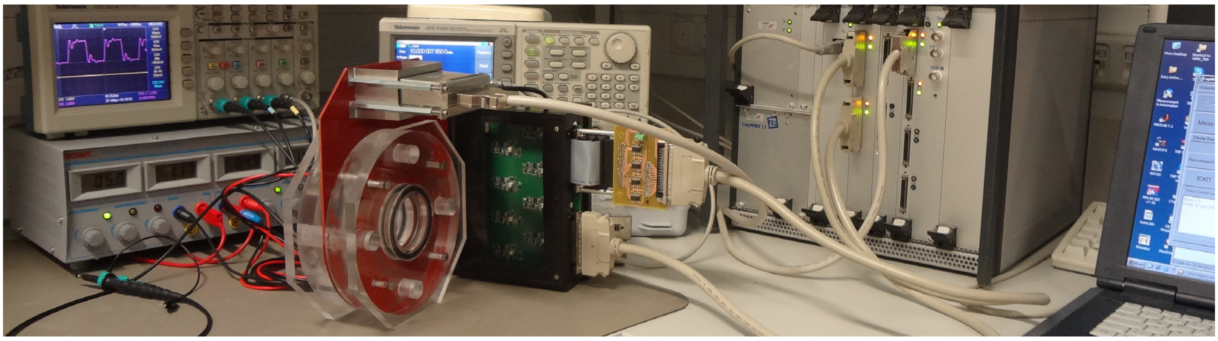
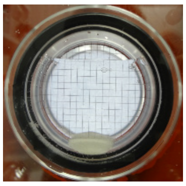
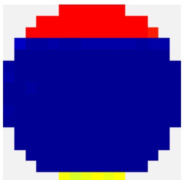
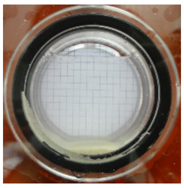
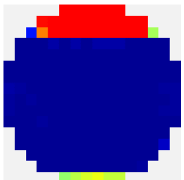
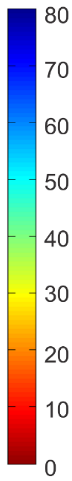
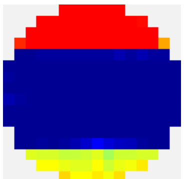
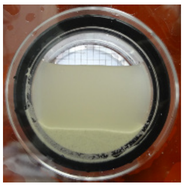
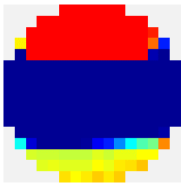
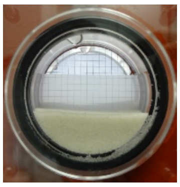
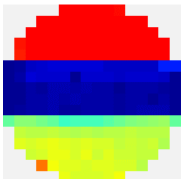
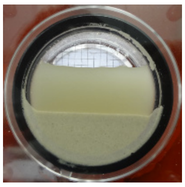
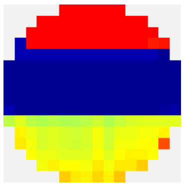


Figure 1. Experimental apparatus with 100 mm pipe segment long and 50.8 mm internal diameter with a wire-mesh sensor 16 x 16 (emitters x receivers) attached to capacitive electronics

Table 1. Cross section images of three-phase liquid–gas–solid flow for different phase fractions.

Sand fraction wt%	40/70 Camera	40/70 WMS	140/270 Camera	140/270 WMS	Permittivity (ε)
3%					
23%					
53%					

After the static test measurement, a further investigation with a three-phase flow was performed at 470 Hz frame rate during 21.35 s. The pipe segment with the stratified mixture was shaken to mimic a dynamic flow. After agitation the pipe segment with sensor was put at rest. Figure 2a shows the experiment for 140/270 sand grain. The stratified structure at beginning is well mixed, as can be observed in the period up to approximately 1.5 s. Then the separation process takes place as the sensor is put at rest. At the end of 17 s, the initial stratified structure is again achieved. For the same time interval Figure 2b shows the experiment for 40/70 sand grain that was repeated three times. Due to its greater weight the separation process takes place faster. The colours representing both sand grains are different due to the gravitational packing. The space between 40/70 sand grains allow more water presence increasing the permittivity at the measured region.

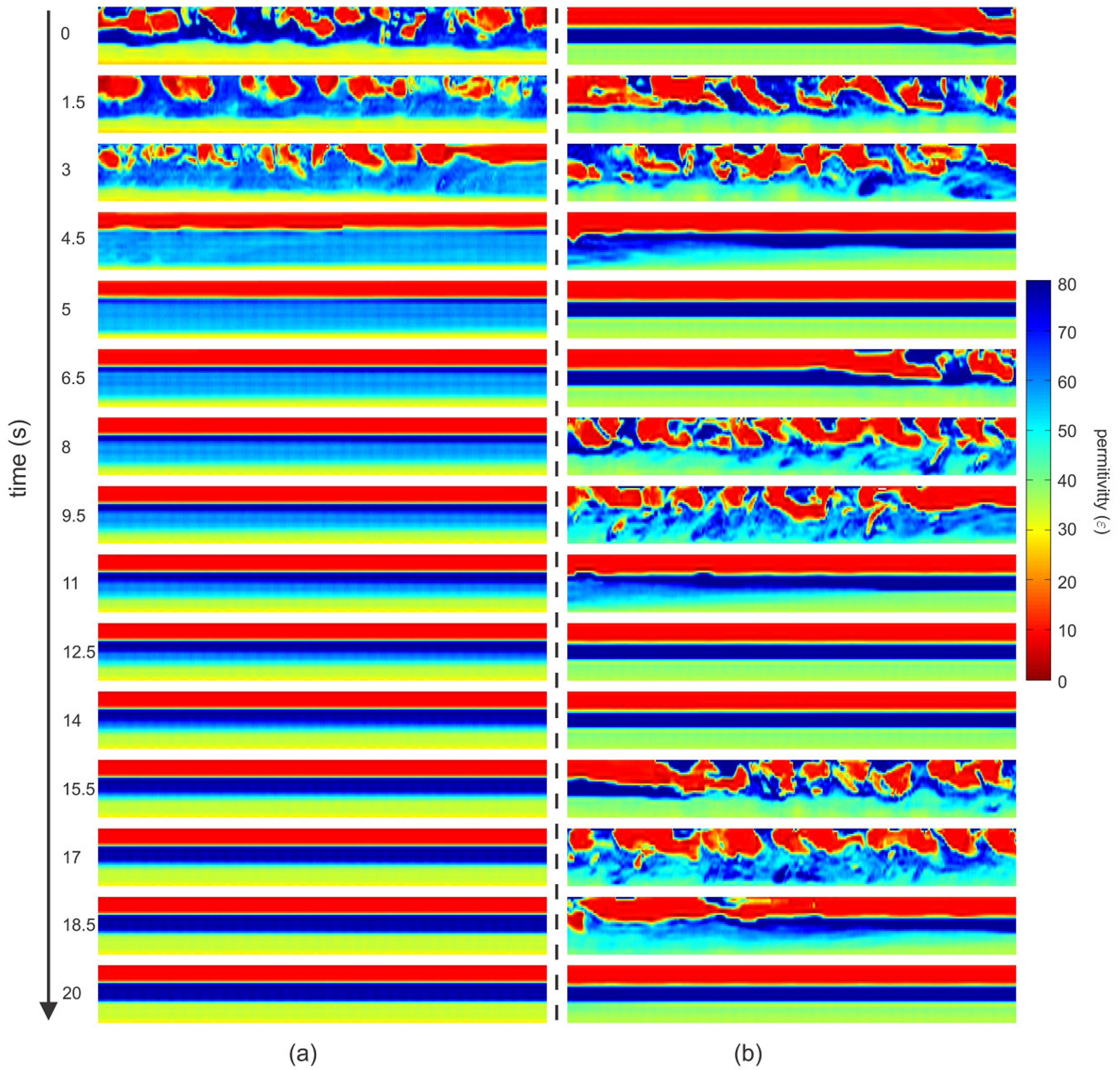


Figure 2. Axial slice images which were produced by taking the values from electrode number 7, i.e. along a central chord of the pipe. Each image represents the measuring time of 1.5 seconds. (a) 140/270 sand grain (b) 40/70 sand grain

4. CONCLUSIONS

In this work the wire-mesh sensor was applied to visualize solids distribution in three-phase liquid–gas–solid flow. Images of solid distribution were generated showing some details of the flow behaviour in and may be detailed investigated in future works. Initially experimental tests have been done to determine qualitative distribution. Further, experimental tests using this technique will be focused to determine solid concentration in three-phase liquid–gas–solid flow. Therefore, future work will contribute to a better understanding of the solid distribution in other applications.

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7. RESPONSIBILITY NOTICE

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