Mass Fraction Measurements in Multiphase Flows Using a Clamp-on PVDF Array

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Abstract— In this paper we present a method for the measurement of mass fractions of iron ore in two-phase flows consisting of water and iron ore particles. The proposed method uses a clamp-on PVDF transmitter and a 12-element PVDF receiver array to measure the excess attenuation of pulsed ultrasound due to the presence of particles. From the measured data we are able to extract a quantity that varies linearly with particle mass fraction in the range from 0 to 13%.

With the proposed method we can measure the mass fraction in whole percent, at a 95% confidence level.

Using an array of receivers we are also able to calculate an attenuation profile over a cross section of the flow, which indicates how the particles are distributed within the flow. This is used to examine how the particle distribution is affected by flow speed, flow meter position, and mass fraction, respectively.

I. INTRODUCTION

Multiphase flows are present in several process industries. The oil and gas industry, the paper pulp industry, and the mining industry, to mention a few examples. In the past years several methods have been proposed for the measurement of different types of multiphase flows. A good overview of existing techniques and approaches, along with discussions about advantages and drawbacks, is given in [1].

In our research project, the main focus is on suspensions of iron ore powder in water. This type of flow is present in the mining industry, where water is used to transport iron ore. One of the most interesting parameters to measure is the mass flow of iron ore. Our approach is to develop an ultrasonic technique for measuring the mass fraction of iron ore, and to combine this with some conventional technique for mass flow measurement, for example the Coriolis flow meter, see for example [2].

Other interesting properties of multiphase flows are the velocities of different phases, the particle size distribution, and the geometrical distribution of particles within the flow. The latter is interesting because it has impact on what methodology to use. It will be shown in this paper, that when the mass fraction of iron ore particles increases, the particle distribution becomes more sensitive to other parameters, such as flow speed and flow meter position. If the particles are not homogeneously distributed within the flow, a local technique, where a small probe is inserted in the flow will give inaccurate results or require a lot of calibration measurements.

In this paper we present a technique, based on pulsed ul-

trasound, that jointly measures the average mass fraction of iron ore and the geometrical distribution of particles along a cross-section of the flow. We use a large ultrasound transmitter and an array of 12 small receivers. Both the transmitter and the receiver array are made of Polyvinylidene Fluoride film (PVDF).

The reason for choosing PVDF film to construct the flow meter is that it is very inexpensive compared to piezoceramic transducers, especially since we needed to build an array with several receiver elements. It is also very flexible, which makes it easy to form when constructing the receiver elements. One of the major drawbacks with PVDF is the low Curie temperature, which makes it virtually impossible to use in environments over 80°C.

This paper is the result of a first study of the feasibility to use PVDF to construct multiphase flow meters.

Fig. 1. PVDF transmitter and receiver array used in the measurements.

II. EXPERIMENTAL SETUP

All measurements were performed using a PVDF transmitter and a PVDF receiver array, see Fig. 1. The transmitter and receiver array were both made from a 28 μ m thick PVDF sheet, metallized with silver ink. The film was manufactured by *Measurement Specialties, Inc, Norristown, PA*.

The receiver array consists of 12 elements, each 5 mm wide and 20 mm long (along the flow direction). The spacing between the receiver elements is about 1.5 mm.

The transmitter and the receiver array was clamped on to the flow system depicted in Fig. 2. The flow meter was mounted perpendicular to the flow direction, with the receiver element 1 at the leftmost position.

Fig. 2. Flow system used in the measurements.

The pulses were sampled using a Nicolet 460 digitizing oscilloscope, at a sampling frequency of 100 MHz, which is more than enough since the bandwidth of the transmitted pulses is less than 10 MHz.

III. THEORY

In this section we describe the theory behind the method and how to use it for on-line measurements of mass fractions and particle distributions.

The proposed method uses pulsed ultrasound in the frequency range between 1 and 10 MHz. A change in the attenuation of sound is the most dominating effect we see when particle mass fraction is increased. A common problem in attenuation-based techniques is to relate the energy of the received pulse to that of some reference pulse, preferably the transmitted pulse. There are several approaches to solve this problem. One is to use a pulse-echo technique with a buffer rod that reflects part of the transmitted pulse. This can then be used to calculate the additional losses caused by the medium. For details about this technique, see [3]. Another approach is to mount a thin layer of PVDF piezo film at the boundary between the flow meter and the measured medium and measure the outgoing energy. This technique can be used either in pulse-echo mode or through-transmission mode. For details, see [4].

For the method presented in this paper, however, none of the above methods are suitable. There are two main reasons for this which we will discuss here, as well as our solution to the problem.

First of all, the receiver elements are not identical, and some calibration needs to be done to compensate for this. Clamping the flow meter onto the pipe causes reflections from pipe walls that also needs to be compensated for.

Furthermore, since the transmitter was manufactured by gluing a sheet of PVDF film to a plexiglass bar, the transmitted energy varies across the surface. Fig. 3 shows an approximation of the sound energy at a distance from the transmitter corresponding to the distance through the flow pipe.

The sound energy was measured with a small piezo ceramic receiver¹ scanning an area above the transmitter.

¹Panametrics XMS310 immersion transducer

Fig. 3. Received energy in pure water, 8 cm from the surface of the transmitter.

These measurements were performed in pure water.

The solution to the problem is that we simply calibrate the flow meter by using the received signals in pure water as a reference. The observed attenuation will then be the excess attenuation compared to pure water. As a measure of this, we introduce the *log-energy ratio*, $LE(c)$ as

$$LE(c) = \ln \left(\frac{E(c)}{E(0)} \right) = \ln \left(\frac{\sum_{n=1}^N p_c^2[n]}{\sum_{n=1}^N p_0^2[n]} \right), \quad (1)$$

where c denotes the particle mass fraction, $p_c[n]$ is a sampled version of the electrical pulse generated by the ultrasound receivers, and $p_0[n]$ is the corresponding measurement in pure water.

The *log-energy ratio* in Eq. (1) is then calculated for all 12 receiver elements, and the average is determined. Furthermore, several ultrasound pulses are acquired at each receiver element. The details about the experiments will be presented in the next section.

IV. EXPERIMENTAL RESULTS

In this section we present experimental results from both mass fraction measurements and particle distribution measurements.

A. Mass Fraction Measurements

The mass fraction measurements were performed with the flow meter mounted 80 cm from the top of the one meter long rectangular flow pipe (see Fig. 2). The liquid temperature was kept as constant as possible, using the heat exchanger in Fig. 2, in order to affect the attenuation of sound as little as possible. The maximum temperature difference throughout the complete measurement series was measured to be 0.8°C. Furthermore the flow speed was kept constant, just high enough to keep the suspension thoroughly mixed. Fig. 4 shows the *log-energy ratio* (see Eq. (1)), averaged over all 12 receiver elements, as a function of the particle mass fraction. Furthermore, 150 pulses were registered at all receivers, given an average over 12 · 150 *log-energy ratios*. The error bars show the 95% confidence interval for the average, see section IV-C.

B. Particle Distribution Measurements

By using a receiver which is divided in 12 elements, we are able to measure how the *log-energy ratio* in Eq. (1) varies

Fig. 4. Average *log-energy ratio* over all receiver elements, as a function of mass fraction.

over a cross-section of the flow. Results from the mass fraction measurements showed that the excess attenuation was not the same over the entire cross-section, which in turn indicated that the particles were not homogeneously distributed in the suspension.

TABLE I
SELECTED LEVELS FOR THE INVESTIGATED FACTORS.

Factor / Level	high (+)	low (-)
mass fraction (A)	10%	2%
flow speed (B)	4-5 m/s	1-2 m/s
position (C)	+	-

In order to test this, a new series of experiments was performed, planned as a two-level factorial design (see for example [5], chapter 10). The factors we assumed were likely to affect the geometrical distribution of particles were *mass fraction* (A), *flow speed* (B), and *flow meter position* (C). For each of these factors (variables) two levels were chosen, one low and one high (see table I). The flow meter position was either near a pipe bend (+) or after 80 cm of straight pipe (-).

This led to $2^3 = 8$ possible combinations. In order to have the pure water measurements to compare with, four additional measurements were needed. Table II shows the resulting experimental design.

In order to compare the results, we need a measure of how the particle distribution varies. Fig. 5 shows the average *log-energy ratio* as a function of the receiver element number, k ($k = 1..12$). We see in Fig. 5 that the attenuation varies over a cross section of the flow. As a measure of this we use

$$\bar{x}(A, B, C) = \frac{\sum_{k=1}^{12} k \cdot \overline{LE}_n^2(A, B, C)}{\sum_{k=1}^{12} \overline{LE}_n^2(A, B, C)} \quad (2)$$

which can be regarded as the mass center of the attenuation

TABLE II
EXPERIMENTAL DESIGN FOR PARTICLE DISTRIBUTION MEASUREMENTS.

No.	A	B	C
1	0	-	-
2	0	-	+
3	0	+	-
4	0	+	+
5	-	+	+
6	-	+	-
7	-	-	-
8	-	-	+
9	+	-	+
10	+	-	-
11	+	+	-
12	+	+	+

Fig. 5. Average *log-energy ratio* as a function of receiver element. The solid and dotted lines correspond to a mass fraction of 2% and 10%, respectively.

profile, expressed in receiver element number. This is then done for 150 pulses, and the resulting mass centers are plotted in Fig. 6. The figure clearly shows that when the flow meter is mounted at the high (+) position (near the pipe bend), the attenuation profile varies much more, regardless of mass fraction and flow speed. This is probably mainly due to the distortion in flow profile caused by the pipe bend.

C. Uncertainty Analysis

In this subsection we analyze the uncertainty in the mass fraction measurements, given the number of pulses measured at each receiver element and the resulting standard deviation.

For each of the 12 receiver elements, 150 pulses were measured for each particle mass fraction. Fig. 4 shows the average *log-energy ratio* taken over all pulses at all receiver

Fig. 6. Center of the attenuation profile for the different experimental settings. The top four are measured close to the pipe bend, while the lower four are measured after 80 cm of straight pipe.

elements, that is

$$\overline{LE}(c) = \frac{1}{12 \cdot 150} \sum_{k=1}^{12} \sum_{m=1}^{150} LE_{k,m}(c), \quad (3)$$

where $LE_{k,m}$ is the *log-energy ratio* for pulse m at receiver k .

The accuracy of the measurement method thus depends on how accurately we can determine $\overline{LE}(c)$ in Eq. (3). A confidence interval for $\overline{LE}(c)$ can be calculated from the estimated variance between different measurements, as

$$\overline{\sigma}^2 = \frac{1}{12} \sum_{k=1}^{12} \overline{\sigma}_k^2 \quad (4)$$

where $\overline{\sigma}_k^2$ is the variance of the measured average *log-energy ratio* at receiver k .

Assuming that the *log-energy ratio* is a stochastic variable belonging to some distribution. Because of the central limit theorem, if we average the *log-energy ratio* over 150 measurements, the average, taken over all replicates and all receivers will be normally distributed with mean $\overline{LE}(c)$ and variance $\overline{\sigma}^2$. Since the mean and the variance are unknown and have to be estimated from the measurements, the resulting confidence interval is given using the *t*-distribution [5].

From measured data we estimated the standard deviation for each of the mass fractions. The maximum value was found to be $\overline{\sigma} = 0.038$. The corresponding 95% confidence interval for the average *log-energy ratio* is then $\overline{LE}(c) \pm 0.076$, which is also plotted in Fig. 4. We can see in the figure that there is no overlap between the confidence interval limits if we limit the measured mass fraction to whole percent.

V. CONCLUSIONS AND DISCUSSION

Experiments show that we, using the proposed method, can extract information from the ultrasound pulses that varies linearly with particle mass fraction. Using an array of receivers we also obtain information about how particles are distributed over a cross-section of the flow. The results indicate that the particles are not homogeneously distributed within the flow, especially not if the flow meter is installed close to a pipe bend. This has implications on which measurement technology to use. A small probe, monitoring only parts of the flow, will most likely give biased results.

In this paper we showed that the attenuation of sound varies over a cross section of the flow, and that the attenuation profile depends on flow speed, flow meter position, particle mass fraction, and possibly other physical properties, which we have not yet examined. Using an array of receivers we can average the measurements over an entire cross section and reduce these effects.

Furthermore, we show that accurate results can be obtained using a simple and inexpensive receiver array, manufactured from PVDF film. The proposed method is completely non-intrusive since the transmitter and receiver array can be clamped onto the flow pipe.

VI. FUTURE WORK

The experiments conducted so far show that the proposed method can be used to measure mass fractions in multiphase flows, once the method has been calibrated. A better theoretical model of how ultrasound is attenuated in such flows, will potentially reduce the amount of calibration needed.

Also, it is likely that the particle distribution is affected by many other factors. In our small experiment we only examined a few, and a natural next step is therefore to extend the experimental plan to include other potential factors.

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