Development of an Online Measurement Apparatus for the Study of Stratified Flow in Near-Horizontal Pipes

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Abstract— **There is a high industrial interest today in the development of accurate measurement techniques to support the modelling of gas-liquid flow phenomena. When dealing with stratified flow in horizontal or inclined pipes, the main problem is that in the range of medium to large gas velocities there are very few data available for the development or validation of flow models. These data should include the measurement of the pressure gradient, the circumferential liquid film distribution, the liquid hold-up and the fraction of entrained droplets. This work describes the development and experimentation of a measurement set-up for generating these data at flow conditions as close as possible to those of industrial interest, in terms of pipe diameter and physical properties of the fluid. This paper focuses on the measurement technique, which is based on conductivity measurements by arrays of needle-shaped electrodes, and illustrates one practical implementation and its validation.**

Keywords— Stratified gas-liquid flow, Conductance probes

I. INTRODUCTION

In many industrial sectors the efficient transportation of fluids requires the precise assessment of a multiphase flow, such as for the pipelines in the oil&gas industry. In particular, the choice of the pipeline diameter is often critical, due to the possible liquid accumulation in the case of low velocities, and the excessive pressure drop in the pipeline at large gas velocities.

In the case of horizontal or inclined pipes, the final choice of the pipe diameter often leads to a flow pattern that can be classified as stratified/dispersed flow (SDF). In these flow patterns, which are encountered for gas velocities above 3-5 m/s at operating pressures in the range 30-100 Bar, due to the effect of gravity, a thick liquid film flows on the bottom of the pipe. The gas velocity is large enough to cause appreciable liquid entrainment, with the consequence that the entrained liquid tends to form a distinct liquid phase able to accelerate almost to the gas velocity, depositing back on the pipe walls. This mechanism may cause an appreciable increase of the pressure drop along the pipeline, which often leads to practical problems.

Thus, there’s a strong interest of the oil and chemical industries for the precise modelling of these phenomena, in order to determine optimal parameters for pipeline transportation. The critical parameters to be measured in SDF conditions are the flow rate and the thickness distribution of the liquid layer flowing at the pipe wall.

Besides the fluid dynamic issue, a better knowledge of the flow behavior, especially in the proximity of the internal walls of the pipeline, has a wide number of implications in heat transfer and flow assurance studies. This objective can be accomplished by designing specific laboratory experiments in controlled conditions, which require the development of dedicated measurement equipment. In particular, non-intrusive or moderately invasive methods for the assessment of the flow patterns are generally based on the observation of some electromagnetic feature of the fluids involved in the process.

One possible approach is to make use of conductive liquids with proper characteristics for simulating real hydrocarbon flow conditions. In this case, measurements can be made with a set of conductance probes, by combining conductance measurements with independent conductivity assessments, in order to estimate the film thickness [1]. This approach also opens the possibility to detect the pattern of the flow velocity, by injecting a conductive tracer.

The sensing technique described in this work consists of a circumferential array of conductance probes made of needle-shaped electrodes, designed to measure the electrical conductance of the local film of liquid.

In this context, an experimental system for the measurement of the thickness distribution of a liquid layer flowing in near horizontal pipes has been developed, as a part of a larger experiment for the simulation of real multiphase flow conditions in pipelines, which will be briefly described later in this paper, being outside our current scope. In this wide framework, this paper focuses on the development of the sensor units, their working principle and their validation.

II. MEASUREMENT TECHNIQUE

A. State of the art

Probes based on wire electrodes have been introduced in various literature examples, starting from the early '70s [2] Further studies about the electrical model of a measurement probe made by wire electrodes were presented by Brown et al. [3]. Flush-mounted electrodes have been first described by Coney [4], which studied the behavior of flat conductive surfaces for the measurement of a film thickness by conductance measurements, already remarking the possibility to align the electrodes with curved surfaces.

Geraci et al. [5] proposed a combination of wire and flush-mounted electrodes for the measurement of the liquid film thickness distribution in a SDF context. Multiple probes made by ring electrodes have been used to study slug flow in inclined pipes [6], proving that a sequence of measurement sections along the pipeline represent an efficient way to monitor slug flow conditions.

A detailed discussion about the signal saturation characterising flush-mounted electrodes at increasing film thickness is reported by Zhao et al. [7]. Conductance probes made by a pair of wire electrodes have been studied also recently by Barral and Angeli [8], reporting negligible disturbances generated by the electrodes to the flow of the liquid and a substantial immunity from saturation problems.

The use of needle probes has been proposed by Da Silva et al [9], showing the feasibility of complex permittivity measurements for investigating oil–water–gas flows. Also, a mesh arrangement of wire electrodes (WMS – wire mesh sensor) is described in [10], where the measurement of conductance is performed by using rectangular excitation pulses. Vieira et al. [11] proposed a WMS to study SDF in a horizontal pipe, where the authors identified a limitation of the method in detecting thin liquid films in the upper part of the pipe. Damsohn and Prasser [12] investigated the issue of thin films by developing specific planar sensors, characterized by high speed and fine spatial resolution, at the expense of saturation at higher film thicknesses.

B. The proposed approach

The main objective in the development of this technique was the measurement of the circumferential thickness of liquid with a wide measurement range, assuring a straightforward and accurate calibration procedure at the same time. In particular, the measurement system had to be usable both for thin films and for higher hold-ups (i.e., fractions of conductive liquid in the interval of pipe under measurement).

The approach that has been identified as the most suitable is based on thin needle-shaped electrodes, plugged into a pipe made of insulating material (a brand of Polyethylene Terephthalate). Each sensor unit comprises a probe assembly, which includes three parallel arrays of electrodes, normal to the axis of the tube, which host 16 electrodes each (needles), distributed in the same angular positions on all the three arrays (Figure 1, from [13]).

In addition, when the film thickness is known, a conductive solution can be used as a tracer to measure the flow rate of a liquid film, by continuously adding the solution to the film and measuring how the pattern of conductance develops at a given film height. Such experiments can be done by using consecutive probe assemblies with tracer injections between them, and can be performed both in developing and in fully developed flow conditions.

As shown in [3], the conductance readings of parallel wire probes, *G*, is proportional both to the local film height, *h*, and to the liquid conductivity, γ:

$$G = k \cdot \gamma \cdot h \tag{1}$$

where k is a constant related to the probe geometry.

The above equation is strictly true only under ideal conditions (homogeneous, planar and infinite medium), but it can be applicable as an approximation in practical conditions where the deviation from linearity is negligible with respect to the other errors introduced by the measurement chain.

In the particular configuration chosen for this experimental setup, three electrodes are used (one per each array); one central electrode imposes an excitation voltage and two side electrodes sink the corresponding current, by closing the measurement loop.

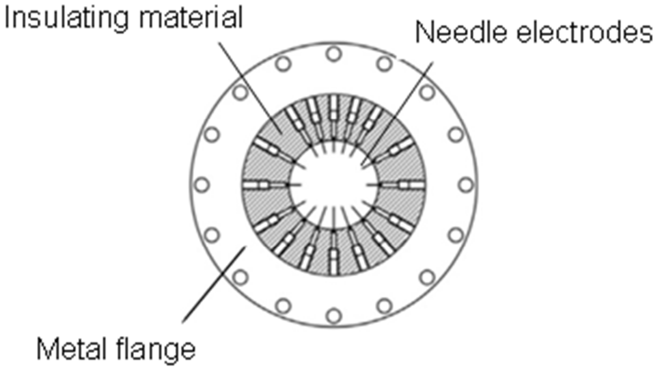

Fig. 1. Cross-section of the electrodes arrangement of each sensor unit.

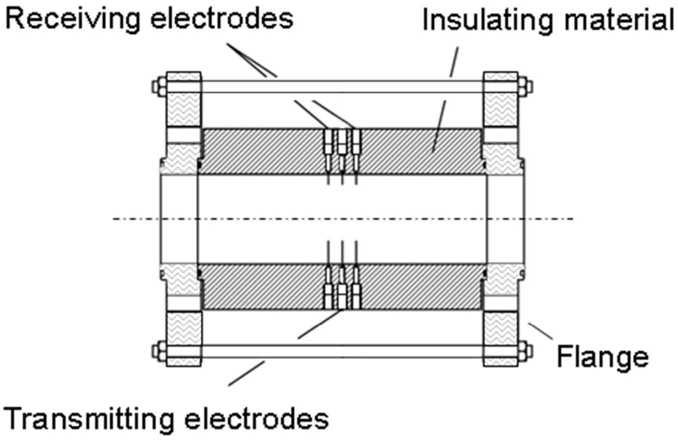

Fig.2. Side view of the electrodes arrangement.

An experimental setup based on consecutive probe assemblies distributed along the flow loop is presented in [14], where the reader can also find a discussion about the electromagnetic model used to estimate current dispersions between adjacent probes and between each probe assembly and external conductors (e.g., metal piping) wet by the same liquid.

A side view of a probe assembly is shown in Figure 2 (modified from [13]), where the installation of the electrodes in the insulating pipe material is highlighted. Each group of three consecutive electrodes put in the flow direction acts as a conductance probe, according to the following criteria:

- a common excitation signal is fed to all the central electrodes (i.e. all the electrodes belonging to central array)
- the two external electrodes are connected in pairs and are actively set to the same potential of all the conductive surfaces of the experimental set-up (i.e. flanges, metal piping, etc.)
- the zero voltage level of the excitation signal is also tied to this potential, which is treated as a voltage reference for the whole analog front-end of the sensor unit
- the observable parameter is the total current flowing into each pair of electrodes belonging to the external arrays (receiving electrodes).

In addition to minimizing current dispersions, this configuration permits to minimize the cross-talk between adjacent electrodes, because nearby electrodes belonging to the same array are actively forced to adhere to the same potential. Also, since the two external arrays are kept in a substantially equipotential plane (tied at the ground potential) the dispersions towards external conductive components of the flow loop are considerably reduced, as demonstrated in [14].

A simplified block diagram of one measurement channel is shown in Figure 3. The excitation signal is generated by a low distortion sinusoidal oscillator, set to a frequency of 100 KHz.

The working frequency has been chosen as a trade-off between the objectives of cutting-off demodulation ripple, make double layer effect negligible, and limit the impact of jitter and switching noise on the synchronous demodulation.

Each pair of receiving electrodes is connected to a separate wideband trans-impedance amplifier, which ensures to tie their potential to the reference potential of the whole electronic front-end. This potential is fully floating, thanks to the galvanic separation of each sensor unit towards its outputs and its power supply. Thus, this virtually equipotential array of current-input electrodes is tied to the same potential of the other electrically conductive wet surfaces of the experimental plant, contributing to the suppression of interferences due to unwanted currents.

The current signals, after being converted to voltage signals, are filtered by a band-pass for the attenuation of both radio frequency interferences and mains hum. Then, signals are rectified by a synchronous demodulator, which is fed by a phase shifted version of the excitation signal by an analog delay line, to compensate for the phase shift introduced by the measurement chain. No appreciable phase rotation is introduced by the medium under measurement, thus, a tunable constant delay proved to be a proper solution for this purpose.

This configuration enables the simultaneous operation of all measurement probes without multiplexing, thanks to the substantial absence of cross-talk between the different probes. The absence of multiplexing represents a noticeable advantage of the present set-up as it enhances signal integrity and the speed of the acquisition.

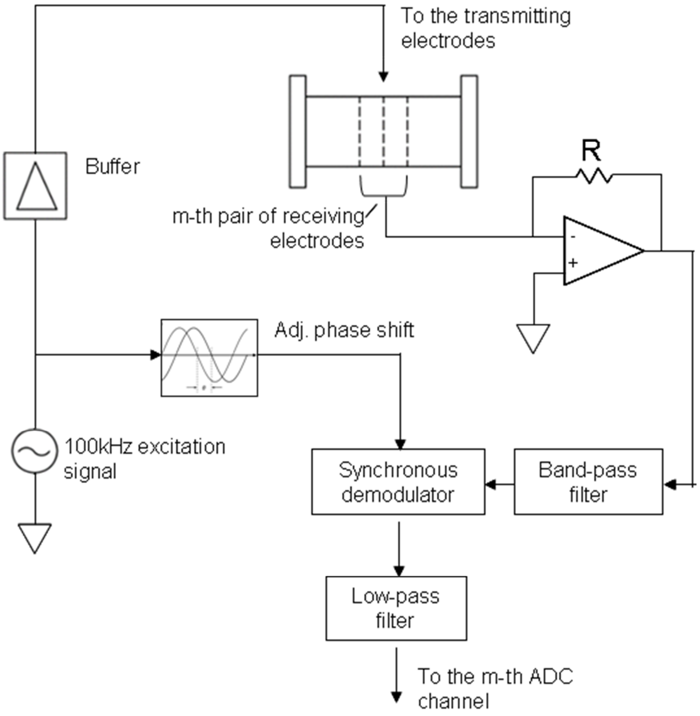

Fig.3. Simplified block diagram of one measurement channel.

III. ARCHITECTURE OF THE SENSOR UNITS

A simplified schematic diagram of each sensor unit and its connections is shown in Figure 4.

The sensor units are part of a larger flow loop designed to operate at a considerable pressure (up to 40 Bar) and composed of metallic pipes electrically connected to the ground potential. Each sensor unit comprises an online sensor assembly connected to the analog front-end as described in Figure 3. Measurement channels have specific features by design and by selection of components (e.g. tight tolerances of passive components, high switching speeds in the demodulator, wide band and low input losses in the amplifiers etc.) in order to maximize the matching between channels onboard the same sensor unit.

In fact, in addition to the said needle electrodes, two dedicated channels are connected with a reference resistor and an independent conductance cell, respectively. Such signals are used to neutralize electrical drifts in the measurement chain by normalizing the acquired signals versus a stable reference, and to compensate eventual changes in the electrical properties of the medium, as it will be further specified in the next section.

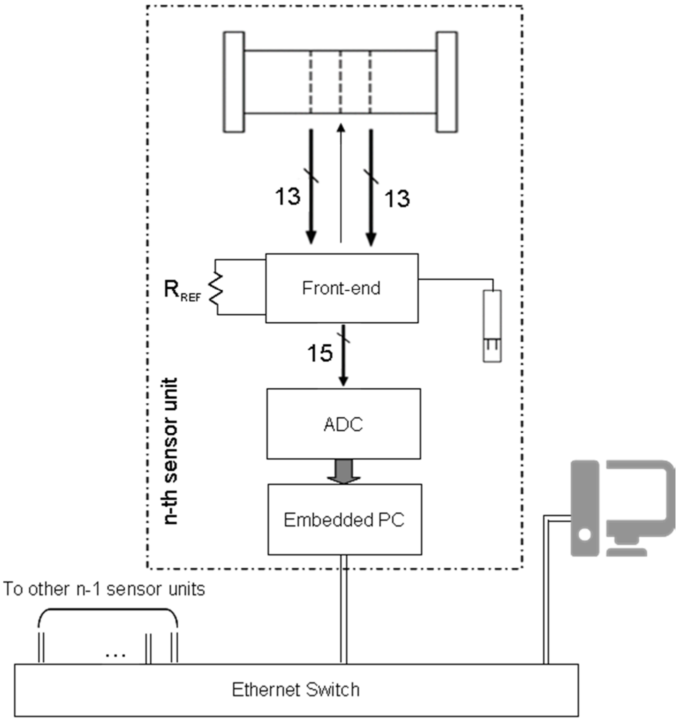

Fig.4. Block diagram of a sensor unit.

Signals are then fed to the Analog to Digital converter, which is contained in an Apex STX104 board, characterised by 16 bits, 16 channels capable of 200 Ksamples/second and ultra low-noise inputs, where simultaneous conversion is done at the rate of 100Hz. The sampling rate has been determined as high enough to observe properly the interesting phenomena, compatibly with the needed rejection of demodulation ripple, which is simply obtained by a 2-nd order passive low-pass filter (Figure 3). A picture of one sensor unit is shown in Figure 5.

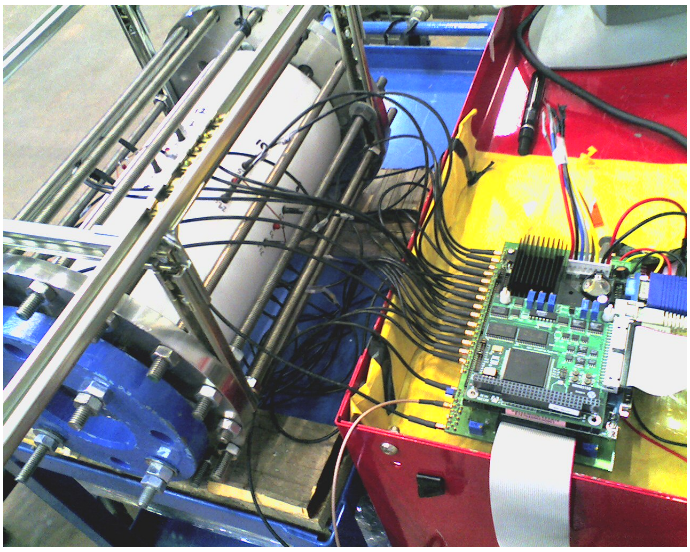

Fig 5. Physical aspect of a sensor unit.

The ADC board is piggy-backed on a CPU board based on a low power VIA Eden chipset, which handles local data acquisition, timing and the handshake with a data concentrator represented by a PC workstation connected via an Ethernet connection. Moreover, an Ethernet switch assures the multiple connections between the said workstation with the other sensor units positioned in the flow loop (Figure 4).

The main features of the software developed are the following:

- online monitoring of data transferred from the sensor units, with real time graphical representation
- data storage and posterior search by using a database interface
- modular design structure for an easy updating and scalability, necessary to deal with modifications and expansion of the whole experimental setup
- access to each single acquisition board with the capability to execute diagnostic tests and download raw data.

The control software is organized in two distinct applications, which cooperate in a Master/Slave mode, being the master running on the workstation PC and the Slave running on each computer board pertaining each sensor unit.

IV. CALIBRATION AND VALIDATION

The collected signals, in order to be converted into information in terms of the wet length of the needle electrodes, undergo a processing phase that is resumed by the following three steps:

i. normalisation with respect to a reference signal (R_{REF} connected to the dedicated input shown in Figure 4)
ii. correction with respect to conductivity variations and temperature effects (by the conductivity cell indicated in Figure 4)
iii. application of a calibration function, as described later in this section.

The wet length of each electrode has to be considered as the output parameter of the calibration process, where the input parameter consists in the normalized and corrected signal, after steps i) and ii).

The reference channel used for step i) makes use of a precision metal film reference resistor, having a sufficiently low temperature coefficient for the purpose (<50 ppm/°C). Its function is to enhance measurement stability after calibration, especially for what regards thermal drifts in the measurement chain, taking advantage by the high degree of matching between channels. Step ii) is also necessary for compensating eventual variations in the electrochemical properties of the fluid, which are expected due to varying experimental conditions.

Thus, calibration data are collected in order to characterise the input/output functions of each sensor unit towards its individual behaviour. In our tests, all the electrodes with the exception of the vertical ones exhibited sufficient linearity to be characterized by a linear calibration function, being approximated by a linear function with $R^2>0.99$ until 1/3 of their physical length, that means wet lengths about 10mm or higher. Moreover, for wet lengths up to the physical length of each electrode (i.e. till 30mm) $R^2>0.98$ has always been obtained.

In the practical embodiment of the proposed sensor assemblies, the two vertical electrodes are replaced by one diametric wire, mounted across opposite walls of the insulating pipe, and it is especially conceived to measure high thickness levels. The internal diameter of the pipe is set to D=80mm. An appreciable non-linearity is expected in such conditions, thus the corresponding probe is characterized by a look-up table (LUT) for its calibration. Each LUT is generated by a piecewise linear spline approximation, by using a set of discrete calibration points as knots. Interpolated data are then regularly sampled to produce the LUT.

The calibration dataset is further validated by comparison with simulation results, in particular by comparing the shape of the input/output functions with the behaviour assessed by the model. In fact, an electromagnetic simulation by a finite elements model was performed preliminarily to the experimental activity. A discussion of the electromagnetic model, its assumptions and the relating results will be presented in dedicated literature, being outside the scope of this paper.

Simulated data from the model are normalised with respect to the value taken at h/D = ½; calibration signals are then projected onto the representation of the model function after scaling according to said normalisation, in order to make possible the direct comparison between the shapes of the obtained curves. Said scaling factor is determined according to a best-fit approach, based on a least-square metric applied to the distance between points of the calibration dataset and the model function.

A very good agreement between the calibration dataset and the simulated data can be appreciated by looking at Figure 6.

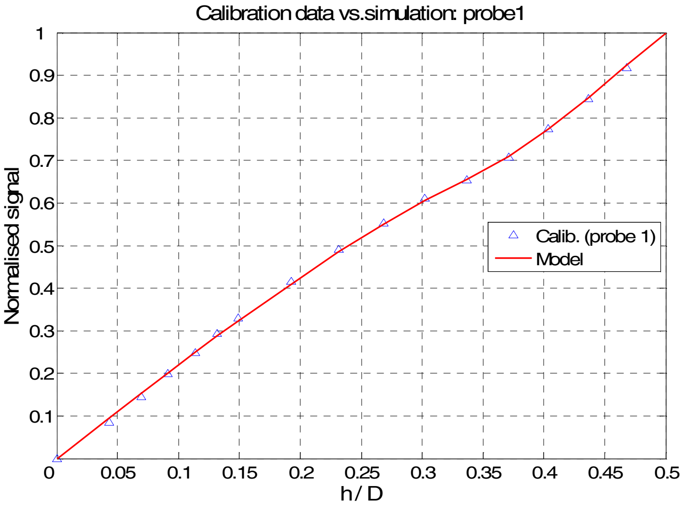

Fig 6. Characterisation of the diametric probe of one sensor unit.

V. CONCLUSIONS

This paper describes the development of a measurement system to monitor in real time how the liquid phase is distributed on specific sections of a pipeline, in particular, the local height of the liquid phase in a stratified flow, or the distribution of the film thickness in an annular flow. The acquisition of such a dataset implies the ability to generate conditions close to a real scenario in a laboratory environment, and to develop an appropriate measurement system.

In the present work, a novel method based on a particular configuration of conductance probes is proposed, in order to measure the circumferential film thickness distribution in stratified flow conditions.

This paper illustrates the measurement technique, which is based on conductivity measurements on arrays of thin needle-shaped electrodes, focusing on the measurement approach, its practical embodiment and the characterisation method. The developed apparatus proved to be effective and permitted to perform several experimental sessions in various conditions, as shown in the companion literature [13] [14]. In particular, the combined usage of flush-mounted ring electrodes and probe assemblies based on needle electrodes permitted to verify the degree of intrusiveness of the needle probes [14].

This experimental set-up can also be adopted to study other flow patterns, such as the flow of liquid slugs or elongated gas bubbles and, in general, developing or transient flow conditions. Given this objective, needle probes appear to be a better choice than flush-mounted probes, due to their intrinsic linearity, which allows the height of both thin and thick liquid layers to be measured at the same time. The main disadvantages of needle electrodes are that they are intrusive and only provide a local value of the film thickness, with the possible consequence of an appreciable uncertainty in the measurement of the average liquid hold-up.

The whole experimental system, in various configurations, permitted more than one year of experiments, thanks to which it's been possible to collect original data as reported in [13].

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