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APPLICATIONS OF WIRE-MESH SENSOR IN MULTIPHASE FLOWS

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ABSTRACT

This article offers an overview of the applications of the wire-mesh sensor (WMS) to different flow conditions. It presents a critical review of the literature, with relevant and recent implementations in gas-liquid and liquid-liquid flow, comparing it with other techniques. Also, it shows how the sensor is adapted to each application, with different geometrical shapes. It indicates the advantages and disadvantages of the use of the WMS. It discusses how the sensor can provide information about local, chordal, cross sectional or volumetric profiles/distributions of phase fraction; velocities, size and distributions of gas/bubbles; frequency of periodic structures; interfacial area; film thickness; flow regimes and thermal distribution. The cost/benefit ratio of the wire-mesh sensor is evaluated.

INTRODUCTION

Measurement techniques in fluid mechanics are a vast field, from a simple LED to multibeam gamma-ray densitometry and from hot-wire anemometry to micro-PIV, the progress has been significant over the last decades. The techniques may be either intrusive or not. It is intrusive if the sensor or part of it is located in the flow path, hence introducing or subtracting energy of the system and affecting the measurement at some degree. Boyer et al. [1] have made an extensive study of different measurement techniques for flow reactors with gas-liquid and gas-liquid-solid flows, covering almost all the techniques, intrusive and non-intrusive. But those authors do not cite the wire-mesh sensor (WMS).

The WMS was first described by Johnson [2] as a sensor for measuring the fraction of water in oil, based on fluid conductivity. Prasser et al. [3] ensured the elimination of crosstalk between the electrodes. It was developed for application in nuclear power plants, in which water-steam flow is subjected to high temperatures and pressures. From there on the WMS is expanding its use in different areas. Recently, Da Silva [4] developed a WMS based on the permittivity of the fluid, which expands the range of substances that can be identified. Also, the wire mesh has been replaced by different shapes [5–11], but the operating principle and the associated electronic circuits are still the same. Overall, the sensor is intrusive, but can deliver a tomographic image with an acceptable cost-benefit ratio compared to other tomographic techniques such as X or ɣ-rays [12].

OPERATING PRINCIPLE

A WMS consists of two or three planes of wires. The wires are parallel in each plane and rotated 90° between planes, Fig. 1 and 2(a). The distance between the planes is of few millimeters or less (0.35 to 3 mm), while the distance between the wires of a plane is a bit higher (0.5 to 15 mm). These planes of wires are placed in the pipe's cross-sectional area. The space between each cross point is filled with fluid. Through a process of switching, each transmitter wire is activated sequentially, i.e., it sends an electrical signal to the fluid. Then, the receiver wire gets a signal that contains the information that identifies the type of fluid at each active cross point. More details on the operating principles of the conductive and capacitive WMS can be found in [3] and [4], respectively. When the sequence of switching for the entire set of transmitters is complete, one slice with the information of the type of fluid or phase fraction on the cross-sectional plane is available, within a time interval. The union of these slices creates a 3D image of the topology of the flow. Also, it is possible to determine several important parameters of the flow from this image.

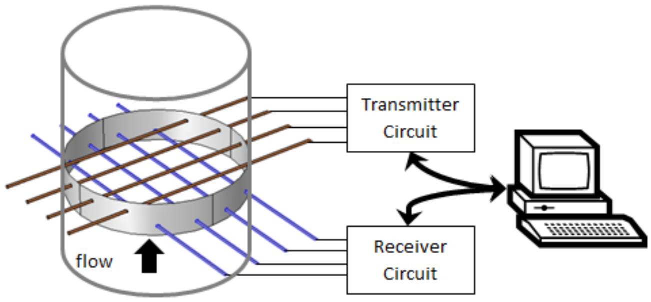


Fig. 1. Schematic view of a normal wire-mesh sensor (WMS) located to obtain the tomographic image in a pipeline.

A derivation of the WMS was developed by Da Silva and Hampel [10], called field-focusing WMS, Fig. 2(b). Especially the wires are changed to long panels. The distance between transmitter and receiver panels is increased by a few centimeters. The liquid no longer flows perpendicular to the planes, but parallel to them and between them, so that the sensor is not intrusive. Therefore, the sensor resembles the devices used in the non-intrusive electrical capacitance tomography, but using the WMS electronics. The measurement obtained between excitation panel and sensing panel is no longer a single point in the duct's cross-section, but it is now an average of the permittivities in the line-shaped space formed by the separation between the planes. This limits the type of flow patterns that could be studied almost exclusively to stratified flow and imposes restrictions on the geometry of the duct. As it senses different transverse planes of the duct it could be used to obtain the phase velocity.

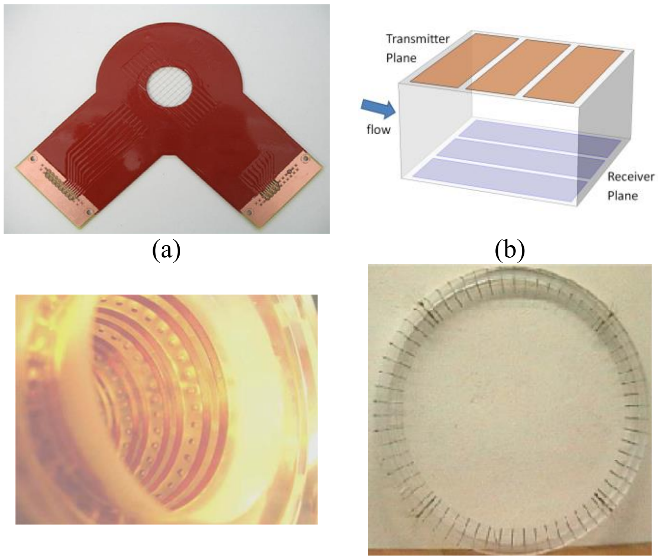
Da Silva et al. [9] proposed the replacement of the wires by small E-shaped capacitors on a PCB. This PCB is placed near a flat wall and it is possible to get a picture of the flow near the wall. Accurate measurements of depth and sensitivity were used to evaluate the system. Moreover, the sensor was applied in the investigation of two different applications. The first was the development in time of the mixing process of two liquids and the second was the analysis of the behavior of a gas being dragged by a jet into a stagnant liquid. Belt et al. [7] performed film thickness measurements in a vertical co-current air/water annular flow in a pipe, Fig. 2(c). The sensor allows measuring the film thickness evolution in time such that the interface of the flow can be reconstructed. Statistics are given for the height, length, velocity, frequency and spatial distribution of the disturbance waves. Also, Damsohn and Prasser [5,6] offered another sensor geometry to be used to measure liquid film thickness. They claim that a much better spatial resolution can be achieved with the proposed geometry. Those authors measured the conductivity of a liquid film in contact with the sensors as a function of film thickness. Information about the dynamics of the surface waves could be obtained, which is relevant for the study of annular gas-liquid flow patterns. The number of wires in the sensor may be diverse, being found from 8×8×8 at three planes [13] up to 64×64 at two planes [14]. The wires not only can be placed in a mesh, also can be placed radially [11], Fig. 2(d).

Types of measurements

The main measurement that can be obtained by the WMS is the mean local conductivity or permittivity, which is directly measured without the need of any inverse reconstruction algorithm, compared to ECT (Electrical Capacitance Tomography). Afterwards, these are converted to local phase fraction [3,15] or concentration/saturation [11,16,17] information. The phase fraction information can be used to derive other characteristics related to different applications. One can see in Table 1 the intended measurement, the description and associated references. A great effort has been dedicated to the validation of the direct measurement of the local phase fraction, chordal profiles and void fraction as well as to the measurement of bubble velocity and size. The promising results suggest the use of WMS for the measurement of more complex variables, as interfacial area, film thickness and topology, thermal distribution and tomography. Prasser reviews in [18] the main papers on data processing.

Limitations

The principal disadvantage of the WMS is its intrusive characteristic. In Passer et al. [3] two types of WMS were used, the first of 16 x 16 wires and the second of 8 x 8 lentil-shaped rods which occupied 4% and 27% of the cross-sectional area, respectively. The corresponding pressure-drop coefficients were of about 0.04 and 0.2 for the former and the latter, respectively. The results indicate that the WMS would cause significant pressure drops. Also, the intrusiveness could generate velocity diminution, bubble-shape distortion, etc., depending on the flow characteristics [19].



(a) (b) (c) (d)

Fig. 2. WMS shapes used in multiphase applications. (a) Normal 8×8 [20]; (b) Schematic view of the Field Focusing sensor 3×3 [10]; (c) Circumferential planar array [7]; (d) Radial measurements 64×4 with detail [11].

The spatial resolution is given by the distance between wires in a plane and wire diameter. High resolution would mean more wires, which in turn increases the occupied area. Furthermore, the wires must bear the drag forces of the flow, so the greater the drag force, the bigger the diameter of the wire. In both cases, the increase of the intrusiveness factor (the percentage of occupied cross-section area) is undesirable.

Other limitations of the WMS are given by the electrical characteristics of the fluids, the number of wires and the input impedance of the receiver circuit. The sensor must ensure that the current through the fluid, in each active cross point, is not diverted to non-active points. This is essentially true if the receiver circuit has input impedance much lower than that of the non-active points, which ideally should be zero. As in practice the impedance is different from zero, it creates a limit to the conductivity (permittivity) and/or the number of receiver wires, e.g., the conductivity WMS, used in [4], requires a continuous conductive phase with electrical conductivity $\kappa > 0.5$ µS/cm.

APPLICATIONS OF WIRE-MESH SENSOR

Single-phase

Water Mixing: one of the experiments in the introductory paper of the planar WMS (Da Silva et al. [9]) is about mixture of plain water with a solution of water-glucose-sodium chloride. The latter is used as a tracer, having higher conductivity. Those authors set a variable called "mixing scalar" which represents a relationship between the measured conductivity and gradients of temperature and density of the substances. They managed to obtain the instant distribution of two miscible liquids.

The works of Walker et al. [22], Frank et al. [23] and Crécy and Debhi [24] form a series of studies on mixing phenomena at T-shaped junctions. Those works include experimental, comparison with CFD and theoretical models. In the experiments two water streams are mixed in a T-shaped union. Conductive WMS are used to obtain the currents' distribution profiles of concentration and speed in the union. It was done at different distances in order to obtain a tridimensional distribution. To differentiate the streams it was used normal water and deionized water with different conductivity values.

Gas Velocity Distribution: Joung et al. [25] showed an application where a single WMS was used to measure gas (air) velocity in a cylindrical container. Those authors used steam as a tracer. It was responsible for changing the sensor's electric current as a function of the water flow rate, which in turn was correlated to the air flow rate. The signals were compared qualitatively with a theoretical model, showing good agreement; but it lacks a quantitative analysis and proper calibration. It is worth pointing out that that work is not clear about the experiment and does not use the conventional model of the electronic circuit for measuring conductivity.

Two-phase

Gas-Liquid: in Hoppe et al. [26] the WMS is used to measure the velocity and angular displacement of gas bubbles dispersed in a turbulent liquid flow. The idea is to use two consecutive WMS and evaluate the data by means of cross-correlation, taking into account the interference on the gas bubbles due to the intrusive wires. The aim is to study the velocity and the angular displacement of the bubbles. The evaluation is done by correlating 3-D data for the velocity analysis and 2-D data taken in cylindrical planes for the angular displacement analysis. The results showed effects of expansion and contraction of the gas phase distribution.

Several studies of steam-water flow are focused on the phenomenon of vapor condensation due to water hammer. Barna et al. [27] modeled the phenomenon and showed that only one of the three simulation codes could simulate correctly the phenomenon. The WMS was used to obtain the void fraction. The work of Strubelj et al. [74] is an extension of the work of Barna et al. Experiments where the transition from stratified to slug pattern is present without the water hammer phenomenon were analyzed. They compared experimental data with two CFD models, with good quantitative agreement, but the models were unable to predict the slug pattern formation.

Recently, Da Silva et al. [28], Abdulkadir, M. [29] and Azzopardi et al. [30] applied a capacitive WMS of 24 x 24 wires to find the distribution of void fraction, the radial profiles, the probability density function of the void fraction data and distribution of bubbles in a co-current flow of air and silicon oil for different superficial velocities of the components. In the work of Silva et al. [28] the results are compared qualitatively with optical images obtained via high-speed cameras. Those authors suggest that the WMS can reveal the internal flow structure that cannot be obtained from optical images. Azzopardi et al. [26] compared the WMS results with ECT and concluded that both techniques deliver approximately the same void fraction. The WMS can provide more details of the bubble size distribution, whereas the ECT can get the speed, because it is not intrusive.

Prasser et al. [31] show the evolution of a gas-liquid flow in a vertical pipe. Those authors study the coalescence and fragmentation of bubbles, and the turbulent diffusion coefficient for turbulent dispersion. Those authors work with a WMS designed for high temperature and pressure. The test conditions was 6.5 MPa and 280 °C for turbulent dispersion.

Ofuchi et al. [32] and Do Amaral et al. [33] studied air-water flow in a horizontal pipeline. The first paper study slug flow, comparing with ultrasound probe. The second compares the results with the Taitel's flow map with good agreement in several patterns. Also, it makes an interesting qualitative comparison with high-speed camera.

Liquid-Liquid: Thiele et al. [8] used the planar sensor to present a simple experiment of mixing of propanol and benzene. The sensor was able to show both fluids at the beginning, take snapshots of the instantaneous distributions during the mixture process and the final homogeneous mixture. Those authors used the Birchak formula [34] for permittivity to check the measurement provided by the sensor, getting an error of 9.1%.

Rodriguez et al. [20, 35] showed the implementation of WMS for the study of drag reduction phenomenon in dispersed viscous oil-water flow in horizontal pipe. Those authors collected a set of data of volume fractions via quick-closing valves and compared it with the WMS results, with good agreement. A significant result of the application is to show that in oil-water stratified flow the interface is not flat, but presents a rather concave shape, Fig. 3.

One can see in Table 2 a summary of the facilities that have used a WMS with two-phase flows and the characteristics of these experiments, including associated reference. The table shows, among others, L: total pipe length, D: pipe diameter and z: distance at which the WMS is placed from the injector. Jg and Jf are the superficial velocities of the gaseous phase (or more viscous) and fluid (or less viscous), respectively.

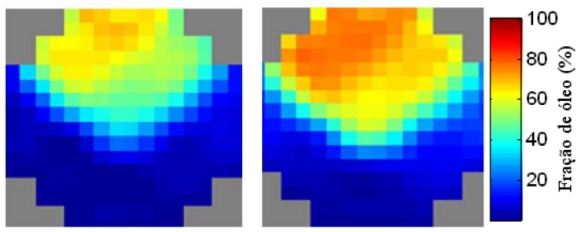


Fig. 3. Phase Distribution in the cross section for the standard semi-stratified dispersed flow [35].

Three-phase

Da Silva et al. [4] introduce the three phase measurement, showing how a capacitive WMS can differentiate between air, water and oil; it is one of the main contributions of this work. Da Silva and Hampel [10] continue showing how it is possible, but with a Field Focusing WMS, only for stratified flow.

Schubert et al. [36] apply several WMS into bed reactors. In that experiment, using four WMS, two are placed closely. Therefore, it is possible to make the measurement of particle velocity using a conductive marker. Those authors assume that the flow has negligible movements in the radial and azimuthal direction. Thus, the measurements may relate to the difference between the permittivity of wire mesh, with the time interval between the measurements and then obtain the flow velocity. As the marker is a conductive liquid, it can affect the correct evaluation of permissiveness in a capacitive wire mesh, but in this case the authors are not interested in that information.

Descamps et al. [37] used a conductivity WMS to obtain the radial profile of phase fraction in a vertical pipe. They used the sensor assuming a two-phase gas-liquid mixture and then separating the liquids into oil and water. The WMS data were compared quantitatively with those provided by an optical fiber probe. Good agreement between both techniques was found in the discrimination of the phase fractions, as long as the concentration of oil in water is small. However, with dense oil-in-water dispersion a large discrepancy between WMS and optical fiber probe was measured.

CFD verification database

Lucas et al. [38–40] obtained an air-water flow database in a vertical tube of internal diameter of 195.3 mm. Two WMS were used in order to obtain the flow velocity. During the experiments, the distance between the injection of gas and plane of measurement was changed to up to 18 different z/D (the relation between the distance to injector and the pipe diameter), using chambers of gas injection at different vertical positions. The pressure was constant at the point of injection of gas, while the temperature remained constant throughout the fluid. Thus, the experiment represents the evolution of the flow along the pipe. 48 combinations of superficial velocities of water and air were tested, ranging from 0.04 m/s to 1.6 m/s and from 0.0025 m/s to 3.2 m/s, respectively. The database allows the determination of profiles of void fraction in the radial axis, distribution of bubble size, volume-fraction profiles decomposed according to radial bubble size and radial profiles of gas velocity. The collected data can be used for the development of closure relations for CFD codes as well as for validation of turbulence models.

Also, the WMS was used to validate the simulation of computational codes as in the case of Höhne et al. [11] with CFX-5 and Trio-U for modeling of a buoyancy-driven flow experiment, and Frank et al. [41] with ANSYS-CFX for water–steam flow in vertical pipe.

CONCLUSIONS

The experimental investigation of multiphase flow is essential for better understanding the flow dynamics and optimization of processes and devices in many engineering applications. This paper presents a review of the operating principle and applications where the WMS can work to obtain flow characteristics. The advantages and disadvantages of the WMS were reviewed and analyzed in several different applications.

This technique shows great adaptability for different types of measurements in a wide variety of applications. On the other hand, it shows good agreement with other methods already consolidated to measure void fraction and velocity of bubbles. In general, it is a technique with good cost-benefit ratio, when facing the same conditions and variables to be measured.

The WMS needs a priori calibration and determination of flow conditions in which it can be applied, to choose the right sensor. The biggest disadvantage of the WMS is the intrusive effect on the flow, for instance it is not possible so far to evaluate the fluid-viscosity limit for its application, followed by the fact that it is not possible to measure the velocity of the phases with a single sensor. On the other hand, the main advantage is the direct measurement of phase fraction without the need of any inverse reconstruction algorithm in flows with conductive or nonconductive fluids. The WMS technique achieves its consolidation when it is used as template of others techniques and CFD simulations.

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Table 1. Types of measurements made by WMS.

Measurement	Description	Reference
Local Phase Fraction, Saturation or Concentration	It measures the proportion in which two substances (fluids generally) are in the cross volume between the transmitter and receiver wires.	[3,4,36,42,43]
Chordal profiles, cross section, volume or distributions of Phase Fraction	Derivation through the integration in time and/or space of local phase fractions.	[15,20,37,42,44,45]
Gas/Bubble velocities	Measured by cross correlation between two WMS, a three-layer WMS or change in the concentration of a tracer. Include angular and lateral displacement.	[22,36,46]
Bubble size and distributions	Obtained through algorithms for bubbles identification, from the local phase fraction.	[47,48]
Frequency of periodic structures	Obtained from identified bubbles / structures.	[32,49]
Interfacial Area	Obtained from identified bubbles.	[50]
Film thickness and topology	The thickness of a conductive film is proportional to the current, in the cross volume between the transmitter and receiver wires.	[5,6,7]
3D images of Volume Fraction Distribution	Reconstructing the 3D volume fraction, placing the sensor at different distances within the volume under analysis.	[45]
Thermal distribution	Measure the temperature by means of thermo- couples placed in the intersection between the transmitter and receiver wires.	[21,51]

Table 2. Facilities that used WMS in multiphase flow applications in pipelines.

Installation / Reference	Application	L [mm] / D[mm]	z [mm]	Jg* [m/s]	Jf* [m/s]	Used fluids	Pressure [MPa]	Temperature [°C]	Studied Patterns	Type of WMS	Spatial Resolution [mm×mm]	Temporal Resolution [fps]
MT-Loop (HZDR) / [42,52]	Multiphase in Vertical Pipe	4000/51.2	6.6-3080	0 - 12	0 - 4.047	Air/Water	atm	30	Bubbly, Slug, Annular	Conductive 24×24 16×16	2×2 3×3	2500 1200
Topflow (HZDR) / [18,50,53,54]	Multiphase in Vertical Pipe, obstacle inside the pipe	9000/195.3	214-7792	0.0025-7.8	0.04-1.611	Air/Water Steam/Water	0.1-0.65	30-259.3	Bubbly, Churn, Annular, Wispy Annular	Conductive 64×64	3×3	2500
Chemical Engineering Laboratory (Nottingham University) / [28,29,49]	Gas-liquid in Vertical Pipe	6000/67	5150	0.047-5,53	0.047-0.2	Air/Water Air/Silicon Oil (low viscosity)	0.32-0.6	15-20	Bubbly, Slug, Churn, Annular	Conductive Capacitive 24×24	2.78×2.78	1000-5000
NETeF (University of São Paulo) / [15,20,35]	high dispersed viscous oil-water in horizontal pipe flow	12000/26.2	9000	0.2 - 1	1 - 3	High viscosity Oil/Water	atm	amb	Stratified Dispersed and Homogeneous	Capacitive 8×8	3×3	500
LACIT (Federal University of Technology - Paraná) / [32,33]	Multiphase in Horizontal Pipe	9200 / 26	7500	0.3 - 2	0.1 - 4	Air/Water	atm	amb	Stratified, Wavy, Slug, Bubbly.	Capacitive 8×8	3.12×3.12	500

* Minimum and maximum velocity used at different experiments.