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Measurement of velocity of gas/solid swirl flow using Electrical Capacitance Tomography and cross correlation technique

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ABSTRACT

One of the big challenges in multiphase flow measurements is velocity calculation. This paper describes utilizing dual-plane Electrical Capacitance Tomography (ECT) to estimate the velocity in case of multiphase swirl flow. A physical model is used in order to simulate the swirl flow phenomena and generate sequences of 2D tomographic reconstructed images. The use of cross-correlation of the signals from the two planes enables the velocity of the gas–solid flows to be calculated. In calculating the cross-correlation, a time-spatial cross-correlation is considered and it allows to perform the cross-correlation in a new way. Different tests were performed, in which the material concentration changes in time was analysed, and the angular velocity component of the flows is presented. The obtained results show the applicability of the approach.

1. Introduction

Flow phenomena are the subject of investigation for many years now, similarly to the development of measurement systems, but the current achieved level of flow process knowledge is still not sufficient from a control point of view [7,19,21]. The importance and significance of this problem are visible in a wide range of industrial installations, where the transport of different material is a crucial element in the production process. In all areas of the industrial environment, from food to petrochemical industry, control of flow is a main problem from both economic and product quality point of view. The high precision of the flow metering unrelentingly is required in order to control precisely the process. An error in flow measurement can cause huge cost losses and efficiency repercussions of the production. Accurate flow measurements and control mainly depend on the correct determination of the flow velocity. The main problem in flow velocity measurement arises when asymmetric and non-uniformities flow profile are observed during the flow [1]. Especially flow behaviour significantly deviating from laminar profile causes a lot of issues for flow metering.

In the case of dynamic multiphase flow, variations in magnitude and direction of velocity are one of the most important issues generating errors during flow measurement [12,17,20,24]. In these cases, the analysis of flow velocity requires more examination of the three velocity components (axial, radial and angular). For laminar flow, where each fluid layer flowing smoothly, parallel to the pipe and without mixing flow structure, the estimation of the velocity profile can be done based only on the analysis of axial velocity. This assumption makes no sense for turbulent flow when the behaviour of the flow structure significantly deviating from the laminar flow is observed. Especially the swirl flow requires an analysis of these three velocity components to determine the swirl angle and to explain the mechanism of the swirl phenomena [6,12]. The significance of the swirl flow measurement very broadly confirms the industrial types of the flow phenomena, where the knowledge about the axial, radial and angular velocity components increase the efficiency of the control system: gas–solid [12], gas–oil [13], combustion chambers [18], cylindrical separators [11] and mixing by agitation [8]. In these situations, the swirl effects are extensively seen as either the desired result of the design or unavoidable and unforeseen possibility as well as side effects for pipe flows during the propagation of the materials.

The development of velocity measurement methods has been conducted for many years. Each progress provides information of better and better quality about the process. In literature there can be found a multitude of papers where methods of measurement are presented and which provide production optimization processes [1,17]. However, the mentioned issues show that accurate measurement of flow velocity in the case of a dynamic swirl flow, as well as flow when it is observed as dynamic spatial and temporal changes of the flow regime (e.g. from laminar to turbulent flow), necessitate further development of the measurement systems.

In order to meet these requirements we propose a method of flow velocity measurement based on statistical analysis of

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Nomenclature

τ	Time shift for cross-correlation
r, θ, z	Cylindrical coordinates
V_r	Radial component of the velocity
V_z	Axial component of the velocity
V_θ	Angular component of the velocity
$x_{[n,m]}, y_{[n,m]}$	Images from two planes of measurement
F_r	Frame rate resolution
$R_{x_{[n,m]}y_{[n,m]}}$	Cross-correlation of the pixels images X and Y
$\Delta\theta$	The angular displacement
d	The distance between the two planes X and Y
Δd	The distance between two pixels (corresponding and best pixel)
T	The time step

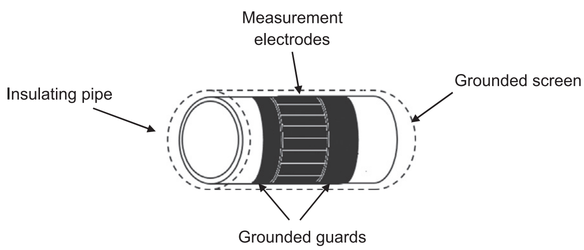

Fig. 1. Structure of a typical ECT sensor.

tomography images, gathered from the Electrical Capacitance Tomography (ECT) system, taking into account the spatial and temporal relationship in the data. ECT is a non-invasive visualization technique based on sensing the differences in the dielectric properties (electric permittivity) of two phases appearing in a flowing medium (e.g. gas and solid). ECT allows visualizing – in the form of an image, the material distribution inside a sensor [9,19,21,24]. For solid–gas flow, e.g. during pneumatic conveying, the gas and the solid phase are characterized by different permittivity values and so the reconstructed image provides information about solid concentration distribution inside the sensor space. A typical 2D ECT sensor consists of a number of electrodes located around a pipe. In Fig. 1a schematic of a one plane 2D ECT sensor is presented. A single image of the spatial distribution of a mixture volume of two materials is reconstructed based on a single set of capacitance measurements – between each pair of electrodes that is taken at the same point in time. All the interelectrode capacitances are measured by application of high accuracy (typically 0.1 fF) and high-speed (typically 200 frames per second for an 8-electrode sensor) acquisition units.

The main advantages of ECT systems are non-invasive measurements; there is no direct contact between the object under inspection and the sensors and there is no change in the characteristics of the explored object while at the same time the acquisition system is capable of such speeds as to control the dynamic industrial process in real-time. These two aspects are very often taken into account during the development of new algorithms for monitoring and controlling units of industrial processes [7,15,19]. In future works the authors will also apply the 3D ECT technique for swirl-flow measurements [3].

In this article, the theoretical considerations concerning swirl-flow-velocity characterization are presented in Section 2. The next Section describes the velocity measurement methods based on the cross-correlation technique and an original method proposed by authors. The validation of the proposed velocity measurement method has been conducted using a physical phantom modelling the swirl flow phenomena, as well as for real data coming from gravity swirl drop measurements (Section 4). The limitations and drawbacks of the proposed model are discussed in the conclusion.

2. Swirl flow velocity characterization

The swirl flow in a pipe can be introduced as a combination of the vortex and axial motions [2,5], with helical streamlines (Fig. 2). In industry application, in order to generate the swirl phenomena the flow is passed through two consecutive out-of-plane bends [2,8]. Swirl generators (swirlers) are used in gas turbine engines, furnaces, burners and cyclones. The swirlers are used in pipes mainly to either enhance convective heat transfer between the fluid and the pipe walls or to intensify mixing, as well as for separation processes. However, the swirl-flow phenomena can also occur in different industry installations without the use of swirlers. From the point of view of this paper, the gas-solid flow in a cyclone separator can be a direct recipient of the proposed method

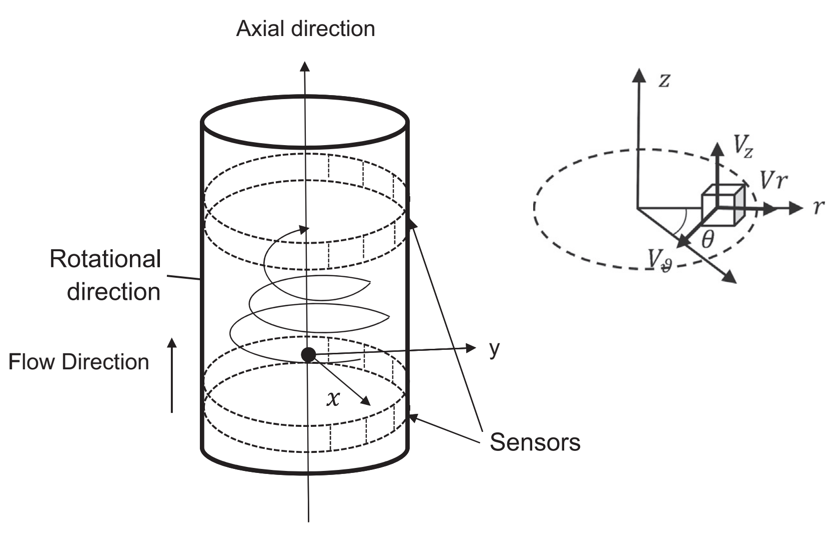

Fig. 2. Twin plane ECT system for flow characterization.