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Study on two-phase flow regime visualization and identification using 3D electrical capacitance tomography and fuzzy-logic classification

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ABSTRACT

From variety of industry-oriented imaging solutions the electrical capacitance tomography applied to the two-phase gas–liquid mixtures visualization and the phase distribution calculation is getting popular especially when flow key parameters are required. Industry demands particularly include efficient non-invasive automatic phase fraction calculation and flow structure identification in the vertical and horizontal pipelines. This can be solved by using non-deterministic fuzzy-logic based techniques for analysis of volumetric images. This paper presents a preliminary study on automated two-phase gas–liquid flow pattern identification based on a fuzzy evaluation of series of reconstructed 3D ECT volumetric images. The set of volume data is obtained by using nonlinear electrical capacitance tomography reconstruction algorithms. Finally a set of fuzzy-based features is calculated for flow substructure classification. As a result of this analysis obtained features will be used to classify given volumetric image into one of known flow regime structures.

1. Introduction

The characteristics of the gas–liquid flow type are very important for the design and implementation of industrial-scale research facility and for the process of the research due to verify achieved results. The continuous monitoring and diagnosing of any abnormalities can provide a valuable information about their dynamic state and allow for continuous and automatic monitoring and control. Two-phase gas–liquid mixtures flows belong to the most rapidly growing trend in fluid mechanics research. In recent years there has been significant, but still insufficient progress in the development of knowledge about these industrial processes. Two-phase flows arouse growing interest because of their great practical significance. They are closely related to the rapidly developing field of research in bioprocess engineering, biotechnology, environmental engineering, energy, and many other related areas. Nowadays based on electrostatic field sensing imaging techniques are mature enough to be used for non-invasive visualization of two-phase flows (Xie et al., 1992) in both: cross-sectional (2D) (Pląskowski et al., 1995; Warsito et al., 2007; Yang and Peng, 2003; Xie et al., 2004), volumetric-oriented (3D) mode (Wajman et al., 2009; Soleimani et al., 2007; Fei et al., 2010) and even real-time volumetric (4D) mode (Soleimani et al., 2009). Formerly conducted research has shown that three-dimensional electrical capacitance tomography (3D/4D ECT) imaging becomes an important tool in industrial processes imaging where the cross-sectional 2D ECT systems provide inaccurate and incomplete information about a process (Yang and Peng, 2003). A lot of work in the field of volumetric capacitance imaging was devoted to the sensing and inverse and forward problem solving techniques development (Wajman et al., 2009; Marashdeh et al., 2007; Soleimani et al., 2007; Banasiak et al., 2010). 3D ECT inspection of two-phase flows is relatively new approach applied to gas–liquid mixtures (Marashdeh et al., 2007; Wang and Zhang, 2009) however these studies focused only on observation of 3D structures of flow by volumetric images reconstruction.

During an industrial process diagnosis, an identifying the flow regime, its structures and determining void fraction is of great importance. In this study to classify the two-phase vertical and horizontal flow regimes, the information obtained from spatial analysis of a set of objects from 3D reconstructed images is used. The fuzzy logic inference will be applied for the first time to the three-dimensional reconstructed images as an efficient evaluator. Classical logic applied for two-phase flow images is based on two values, usually represented by 0 and 1, or terms true and false. Using them we can classify flow as liquid or air regions (ex. air bubbles). The boundary between them is more or less clearly defined and constant. Fuzzy logic approach is an extension of classical reasoning which intention is to be 'more human' (Dubois and Prade,

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1980). It introduces standard values between 0 and 1; it fuzzifies (blurs) the crisp boundaries, giving them the possibility of assigning values between this range (i.e. almost false, half true). In this paper, the uncertainty (values between true and false) can be transposed to gas/liquid 3D reconstruction in which every point can be considered as only liquid, only gas and a state between them. There were few earlier research works in this field with use of fuzzy logic (Ji et al., 2004; Shi, 2008) and without use of fuzzy logic (Zhou et al., 2008; Wang and Zhang, 2009), however this research work only partially considers spatial nature of the sensor (Li et al., 1992).

According to the current state-of-the-art authors did not found direct research on two-phase gas–liquid mixtures flow pattern recognition studying combination of fuzzy logic and volumetric 3D ECT images.

2. Key problems of two-phase gas–liquid flows diagnosis

The two-phase gas–liquid flows are very important component of many industrial processes (Pląskowski et al., 1995). There are few possibilities for potential industrial application of electrical tomography based diagnosis and monitoring system. Therefore it can be applied for investigation of aeration processes in chemical reactors, flotation processes, water and sewage aeration systems. The main task of aeration systems is to produce a proper fraction of aerated liquid and oxygen. Oxygen injection process is important due to the fact that liquid circulation has to be achieved. It helps intensifying a mass transfer process. One of the fundamental problems is proper evaluation of inter-phase interface – there are really important parameters from the mass transfer point of view. The example of water and sewage aeration may be biological sewage treatment plants. Important role in these processes play an aerobic bacteria (aerobic), that grow only in the presence of free oxygen from the atmosphere or dissolved in water (Pląskowski et al., 1995). The level of aeration must be within the specified range, which depends on water temperature. One way of aeration is to inject into the system, compressed air, making the need for freedom of gas bubbles movement in the liquid column up. The two-phase flow processes also occur in bubble columns. Their purpose is to implement the various physical and chemical processes. Controlling the size of the interface often determines the intensity of these processes progressing. For example, in air-lift columns and ejectors (Pląskowski et al., 1995) the movement of the liquid stream is forced by the gas stream. Such devices are commonly used in the extractive industries (e.g. flotation processes) or to precipitation of some fraction of the liquid in the sedimentation processes, such as degreasing where the size of bubbles is significant. There is also a separate group of industrial processes in which gas bubbles may be formed in the liquid as a result of chemical reactions. It can occur for example in chemical reactors or in the process of electrolysis, where the gas phase is a product (often a by-product) of a chemical reaction. Then the appearance of bubbles indicates the quality of ongoing changes, and measurement of bubble size provides information about the process. There are industrial processes in which the occurrence of bubbles is undesirable, such as heat exchangers or heating devices. In these systems the appearance of unwanted gas gives evidence of boiling liquid phenomenon, and enforces state of emergency signaling. This occurs similarly to cavitation phenomena in rotational pumps, which are caused by a rapid decrease in pressure below the pressure of the boiling liquid. This phenomenon is undesirable because it leads to erosion of the blades of the pump. This phenomenon could also be the evidence of system leakage. One of the fundamental problems where knowledge of which is necessary to describe the hydrodynamics of two-phase flow mixtures include: determination of the mixtures of two-phase flow patterns, determination of the void fraction in the flowing mixture and the flow resistance of mixtures. In addition to the description of mass transfer in two-phase flow systems we need to know the interfacial surface area, coalescence of gas bubbles and mass transfer coefficient. So far, none of these issues have been satisfactory presented in the literature (Chhabra and Richardson, 1986). This is due to the complicated mechanism of flow dynamics, often connected with difficulties in its description from the mathematical point of view and it is connected with complicated measurement methods typically used in the two-phase flows study. One of the main challenges in the two-phase flows is a possibility of a priori prediction of the characteristics and the type of mixture flow on the basis of known values of apparent velocity and the properties of individual phases, and the flow geometry (diameter and angle of wire, placement and shape of structures). There are different observation techniques of resulting mixture flow structures developed by various research teams. It varies from the simplest visual observations by different techniques for photographing and filming through the opto-electronic detectors to the newest methods of using two- and three-dimensional computed tomography (Xie et al., 1992; Pląskowski et al., 1995; Xie et al., 2004; Marashdeh et al., 2007; Warsito et al., 2007). The most commonly observed structures of the gas–liquid mixture flow in the pipes of the vertical ascending movement are consistent with those presented in the past (Nicklin et al., 1962). These structures generally classify this type of flow. There are five basic flow patterns known: bubble flow, slug flow, foam flow, ring flow and dispersion flow (as can be seen in Fig. 1). These flows can be succinctly characterized as follows:

- Bubble flow occurs when gas bubbles are dispersed in the liquid stream that fills the entire cross section and their speed is close to the speed of the liquid.
- Slug flow occurs when large bubbles of gas, typically with a diameter similar to the diameter of the pipeline flow alternating with portions of the liquid which additionally may be tiny bubbles of gas,
- Foam (churn) flow is usually defined as a oscillatory and unoriented – this is the chaotic flow of two phases creating a rare form of resembling foam.
- Annular flow is when the gas flows at high speed in the central part of a pipe while the liquid forms a thin layer adhering to the walls of the pipe.
- Dispersed flow occurs when the gas stream flows around the wire carrying the cross-tiny liquid droplets.

The ranges of the various flow patterns occurrence are typically presented on the graphs and called as flow maps. The area of such plots – which are made in different coordinate systems – is divided on the lines demarcating the subareas where the given structure of flow exists. The concept of boundary lines means certain narrow band of flow map area. In real world of flows there are no sharp

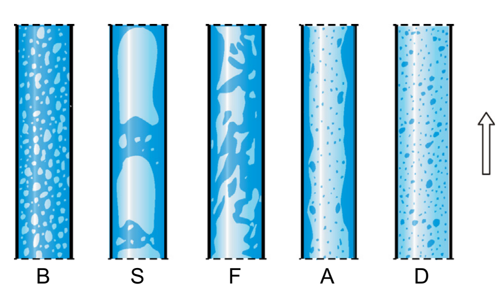

Fig. 1. Two-phase flow structures in bottom-up vertical direction (B – bubble flow, S – slug low, F – foam flow, A – annular flow, D – dispersed flow).