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A dual-modality electrical tomography sensor for measurement of gas–oil–water stratified flows

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ABSTRACT

Multiphase flow measurement is a challenging work, especially for the measurement of gas–oil–water flows. In the past, researchers tried to measure gas–oil–water flows by using two separate electrical tomography (ET) sensors, e.g. electrical capacitance tomography (ECT) and electrical resistance tomography (ERT). In this paper, a typical ECT sensor with inner electrodes, as an ECT/ERT dual-modality sensor, is investigated for the measurement of gas–oil–water stratified flows. With this ECT sensor, the voltage-excitation and current-measurement strategy is adopted for both ECT and ERT measurement unlike the conventional ERT with current-injection and voltage-measurement, which cannot provide quantitative measurements because of serious fringe effect. To validate the effectiveness of the proposed measurement strategy, experiment was conducted with an impedance-analyser-based data acquisition system, which can take both capacitance and conductance measurements simultaneously. Based on the measured capacitance and conductance, the corresponding permittivity and conductivity distributions can be reconstructed for the same cross section. A simple data fusion method is proposed to extract the information regarding the oil distribution from the reconstructed images, which was proved to be effective. In the experiment, different excitation frequency and different conductivities of the water phase were examined to investigate their influence on the three-phase flow imaging and measurement. The proposed measurement strategy has advantages of simplified sensor design, reducing the complexity of the related electronics as well as acquiring all information from the same cross section.

1. Introduction

Electrical tomography (ET) has been developed for more than two decades. As two most conspicuous ET techniques, electrical capacitance tomography (ECT) and electrical resistance tomography (ERT) have been extensively investigated and widely applied in various industrial applications involving multiphase flows for real-time monitoring and control of related processes [20,18,4,21]. As a single modality, ECT can be used to image dielectric processes, i.e. the permittivity distribution, through capacitance measurement, while ERT can be used to image conductive processes, i.e. the conductivity distribution, through resistance or conductance measurement. However, most ET systems are based on measuring a single electrical property, e.g. either permittivity or conductivity, which have limitation in the measurement of complex multiphase flows, e.g. gas–oil–water flows. York [20] pointed out that it would be beneficial if the capacitive and resistive properties of components in a multiphase flow can be measured simultaneously, which would provide more comprehensive information about the corresponding process. Therefore, effort has been made to design multi-modal (e.g. ECT/

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ERT) tomography systems in recent years [5,14,11,2,10,12,13,15,3].

Hoyle et al. [5] investigated the design and application of a multi-modal system, incorporating ECT, ERT and ultrasonic tomography (UST). Several aspects of the system design, enabling data fusion and interpretation, were examined, including the challenges for the hardware design and the requirements for the software design. To validate the multi-modal system design, trials were conducted for integration and interpretation of the synchronised data from different tomographic modalities and auxiliary non-tomographic data. In this work, the ECT, ERT and UST sensors were arranged at different cross sections along a pipeline. Qiu et al. [14] described the engineering and application of an ECT/ERT dual-modality system. The performance of this system was tested in a range of applications, e.g. imaging fluidised bed and bubble column, visualising three-phase distributions, and deriving information about the flow patterns, flow regime and the phase velocity of different gas–water and gas–oil two phase flows. In this system, the ECT and ERT sensors are still located in different cross sections of a pipe. More importantly, because of the fringe effect, the conventional ERT cannot provide quantitative measurements. Cui et al. [2] proposed an integrated ECT/ERT dual-modality system with both two sensors mounted in the same cross-section and intended to measure the dielectric and conductive distributions in the same cross-section for a multi-component process. Experiment was carried out for different two-phase flows in a horizontal or vertical pipe. Li and Yang [10] discussed the necessity and development of multi-modality tomography systems and carried out some initial simulation and experiment to investigate the feasibility of an ECT/ERT dual-modality system with a voltage-excitation strategy, and some promising results were obtained for the measurement of several typical multiphase flows. In this system, two separate sensors were used for ECT and ERT measurements, respectively. Sankowski et al. [15] and Nowakowski et al. [12] presented the design and application of a system for measuring phase fractions in a multi-phase flow, combining ECT or ERT with measurements obtained simultaneously from gamma sensors. All the sensors were arranged at the same cross section along a pipeline, and the choice of ECT or ERT or their combination depends on the type of mixture to be measured (conductive or non-conductive). The data from the gamma sensors was used to correct the reconstructed distribution based on ECT or ERT, which was finally used to determine the component fractions in a flow. Good experimental results were given with their designed system for measuring a series of multi-phase flows. In this system, ECT and ERT measurements were acquired using two separate sensors. Deng et al. [3] suggested a multi-modal (ECT, ERT and electro-dynamic) sensor for measuring the concentration and superficial velocity of solids in a gas–solids two-phase flow (configured as an ECT/electro-dynamic dual-modality system) and the distribution in a gas–liquid two-phase flow (configured as an ECT/ERT dual-modality system). Some initial results were given. In this system, the ECT/ERT or ECT/electro-dynamic sensors were placed in different cross sections along a pipe.

When two ECT and ERT sensors in a dual-modality system are mounted in different cross sections of a pipe, dielectric and conductive properties of a multiphase flow can be measured simultaneously. However, it is necessary to synchronise the measurements between the two sensors for data fusion [5,14] and this type of system is not suitable for the measurement of a highly dynamic flow since the flow pattern would vary from one cross section to another along the pipeline [2]. When ECT and ERT sensors are located in the same cross section, synchronisation is not needed, but the dielectric and conductive measurements can be taken sequentially only to avoid the mutual interference between the two excitation signals [2,10]. Marashdeh et al. [11] provided a solution to this dilemma. They proposed a multi-modal system based on an ECT sensor with electrodes mounted on the outer surface of a pipe, measuring capacitance for permittivity imaging and measuring power balance for conductivity imaging. With this system, multi-modal measurements can be taken in a non-invasive way and the results for the specified two-phase flows are promising. However, there is no evidence that this system can be applied in the situations with conductive background medium since the background medium was always set to be non-conductive in their experiment. Another alternative solution is to employ a dual-modality system based on an ECT sensor with electrodes mounted on the inner surface of a pipe, denoted as interior electrodes, for both ECT and ERT measurements, as suggested by Sun and Yang [17]. Up to now, however, almost no experimental result has been reported on the application of this kind of dual-modality sensors for measuring complex multiphase flows, e.g. gas–oil–water stratified flows. This paper presents some experimental results on this topic using an impendence-analyser-based ET system.

With an integrated dual-modality sensor mentioned above, the ERT measurements need to be taken by using the voltage-excitation and current-measurement strategy, as suggested by Sun and Yang [17], instead of the conventional current-injection and voltage-measurement strategy [5,14,2,13,3]. This means that the same excitation strategy is used for both ECT and ERT measurements. Consequently, the sensor design would be as simple as suggested by Marashdeh et al. [11], and the potential interference between two separate sensors or two measurement signals is avoided. Thus more spatially and temporally closely correlated ECT and ERT measurements can be acquired. The related electronics can be designed in a similar way to the impedance analyser, i.e. by separating capacitance and resistance measurements from the measured signal based on phase demodulation. Due to the use of interior electrodes, this dual-modality system can be applied in the situations with conductive background like saline. A drawback is that the ECT measurement becomes invasive, compared with the design by Marashdeh et al. [11]. Due to this invasive configuration of electrodes, however, the negative influences of the pipe wall on the ECT measurements for high permittivity materials, e.g. water or saline, can be eliminated [8].

It has been realised that an ECT/ERT dual-modality system has the potential to measure gas–oil–water stratified