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An electrical impedance monitoring method of water-lubricated oil transportation

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ABSTRACT

We propose a simple and efficient monitoring system based on a single-drive interleaved electrode impedance technique that provides cross-sectional images for real-time detection of fouling in oil–water flows. The simple monitoring method is proposed using a data-interface formula relating between voltage differences measured at sensing electrodes and interfaces of the two immiscible fluids in a pipeline. We estimate the minimum distance between the interface and pipe wall at the images, that is an indicator for monitoring the fouling, by using a voltage–distance map. The robustness of the proposed method is validated through various numerical simulations including oil–water flows in an U-bend return pipe.

1. Introduction

Oil–water flows with high-viscosity ratio have recently attracted much attention owing to the increase of exhaustion of light oil reserves and the depletion of on-shore oil fields. For heavy and extra-heavy crude oil transportation, water-lubricated transport re-emerges as an energy efficient technology in the last few decades in order to reduce pressure drops as well as pumping powers. Since annular water-film along the pipe wall prevents the oil from a direct contact with the wall, the wall friction mainly arises due to flow of water only [1,2]. This flow is known as a core-annular flow (CAF) that consists of a core of highly viscous fluid surrounded by a thin layer of lower viscous fluid [3,4]. One of the major challenging issues in the use of CAF based heavy oil transportation is to retain the water film at the pipe wall or to avoid fouling of the oil [1]. A removal process of high viscous oil that sticks to the pipe wall during shut down is needed for mitigating undesirable higher pressure drops in the pipeline when the fouling occurs. Pre-detection or real-time detection of the fouling is very important for operating the heavy oil transportation using CAF technique without an intervention for restarting the process. Moreover, the recent experimental and numerical studies [5–8] reported that the chances of fouling in oil–water flows through a return bend such as U or Π bend for pipefitting become higher unless proper operation conditions for the CAF are provided. Therefore, monitoring of the fouling is necessary in CAF technique to optimize and control its operation conditions.

Process tomography has been widely used in visualizing multiphase flows such as oil–gas or oil–water flows in industrial pipelines. It provides real-time cross-sectional images of the distribution of materials [9]. Electric capacitance tomography (ECT) has been used for process tomography where external capacitance measurements are used to produce the cross-sectional images of permittivity distribution inside the pipeline [10–17]. This technique enables to visualize the contents of a process vessel or pipeline that contains dielectric materials and non-conducting continuous phases. ECT has several advantages such as non-intrusiveness, simple manufacturing, and low cost. However, in the case of conducting working fluid being in contact with the boundary of the pipeline, ECT may not be appropriate to visualize the water-lubricated oil flows. This is because the insulated oil flow may be poorly detected by the capacitance sensors due to the conducting water.

On the other hand, electrical impedance tomography (EIT) can be a promising technique for monitoring the distributions of the non-conducting materials inside pipelines. EIT provides images of both conductivity and permittivity distributions of internal objects from current–voltage measurements at the boundary of pipeline. EIT method uses multiple current injection pattern to produce electrical current density distribution in the entire region so that Ohm's law can be used to provide tomographic image [18–20]. However, the standard EIT method is not suitable for the water-lubricated oil flows, because the injected electrical current flows only near the boundary of the pipeline and the current cannot

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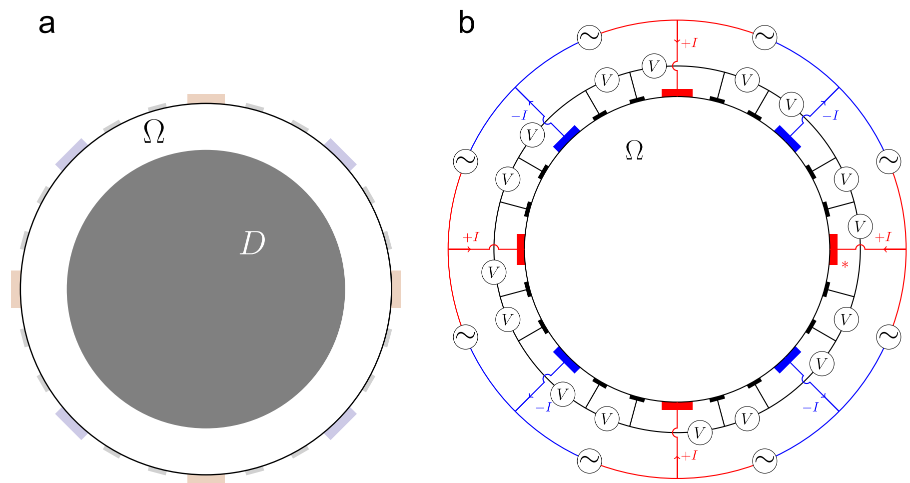

Fig. 1. (a) Schematic of a core-annular flow configuration in cross-sectional view. The region D is initially filled with heavy oil, while the rest of domain Ω is with conducting water. (b) Schematics of electrode configurations for the proposed EIT system. Note that black rectangles on the boundary indicate sensing electrodes while red and blue rectangles represent driving electrodes of inward and outward electric current, respectively. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

penetrate into the insulated oil region. Indeed, we are only interested in detecting the water–oil interface near the boundary of the pipeline.

For monitoring CAF, we design a simple and efficient monitoring system which can be viewed as a modified version of EIT system. The proposed system uses a single-drive interleaved electrode system, as shown in Fig. 1 which measures the voltage difference through sensing electrodes to probe the interface of D. We found a data-interface formula relating between the interface of D and measured data, which provides essential information of detecting the interface. Based on the data-interface formula, we develop a simple method of monitoring the interface of a continuous two phase flow in the pipeline. The minimum distance for the interface from the pipe walls is estimated for monitoring the fouling based on a voltage–distance map. Various numerical simulations validate the robustness of the proposed method in visualizing the interface and estimating the minimum distance.

2. Method

2.1. Mathematical model

In this section, we describe a mathematical model for the proposed EIT system shown in Fig. 1. Let Ω denote a cross-sectional region in the pipeline. For water-lubricated oil flows, the oil and water regions are defined as D and $\Omega\backslash D$, respectively, as in Fig. 1(a). The boundaries of the domain Ω and D are denoted as $\partial\Omega$ and ∂D, respectively. We assume that the oil region is insulated while the water region is highly conductive. As shown in Fig. 1(b), we attach N driving electrodes for injecting current and $2N$ sensing electrodes for measuring voltage along the circumferential direction of the pipe in such a way that the two sensing electrodes are placed between the driving electrodes.

We inject currents of I at the driving electrodes so that the induced voltage u inside the cross-sectional domain Ω is governed by

$$\begin{cases} -\nabla^2 u = 0 & \text{in } \Omega\backslash D, \\ \int_{\mathcal{E}_j^d} \mathbf{n}\cdot\nabla u \, ds = I & \text{if } j \text{ is even}, \\ \int_{\mathcal{E}_j^d} \mathbf{n}\cdot\nabla u \, ds = -I & \text{if } j \text{ is odd}, \\ \mathbf{n}\times\nabla u = 0 & \text{on } \left(\bigcup_{j=1}^{N}\mathcal{E}_j^d\right)\cup\left(\bigcup_{k=1}^{2N}\mathcal{E}_k^s\right), \\ \int_{\mathcal{E}_k^s} \mathbf{n}\cdot\nabla u \, ds = 0 & \text{for } k\in\{1,2,\dots,2N\}, \\ \mathbf{n}\cdot\nabla u = 0 & \text{on } \partial\Omega\backslash\left(\left(\bigcup_{j=1}^{N}\mathcal{E}_j^d\right)\cup\left(\bigcup_{k=1}^{2N}\mathcal{E}_k^s\right)\right), \\ \mathbf{n}\cdot\nabla u = 0 & \text{on } \partial D, \end{cases} \tag{1}$$

where $\mathcal{E}_j^d$ is a driving electrode for $j = 1, 2, \dots, N$ and $\mathcal{E}_k^s$ is a sensing electrode for $k = 1, 2, \dots, 2N$. One pair of sensing electrodes $\{\mathcal{E}_{2j-1}^s, \mathcal{E}_{2j}^s\}$ are placed between one pair of driving electrodes $\{\mathcal{E}_j^d, \mathcal{E}_{j+1}^d\}$, as shown in Fig. 1(b). We measure voltage difference $V_k = u|_{\mathcal{E}_{k+1}^s} - u|_{\mathcal{E}_k^s}$ between two electrodes $\mathcal{E}_{k+1}^s$ and $\mathcal{E}_k^s$. The measured data set $\{V_1, V_2, \dots, V_{2N}\}$ is used to reconstruct the shape of ∂D.

2.2. The relation between the data and the interface

In order to estimate the interface of D from the data $\{V_1, V_2, \dots, V_{2N}\}$, we introduce the computed reference data U_k^0 defined as

$$U_k^0 := I\left(\sum_{j=\text{even}} u_k^0\Big|_{\mathcal{E}_j^d} - \sum_{j=\text{odd}} u_k^0\Big|_{\mathcal{E}_j^d}\right), \tag{2}$$

where $u_k{}^0$ is the solution of the following equations for $k = 1, 2, \dots, 2N$: