Flow Measurement and Instrumentation 41 (2015) 90–96

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

journal homepage: www.elsevier.com/locate/flowmeasinst

Analytical investigation of an inductive flow sensor with arc-shaped electrodes for water velocity measurement in two-phase flows

Y.Y. Shi*, M. Wang

School of Physics and Information Engineering, Henan Normal University, Xinxiang, China

A R T I C L E I N F O

Article history:
Received 13 September 2013
Received in revised form
23 October 2014
Accepted 29 October 2014
Available online 8 November 2014

Keywords:
Inductive flow sensor
Arc-shaped electrodes
Analytical analysis
Two-phase flow

A B S T R A C T

An inductive flow sensor with spot-shaped electrodes (IFS-SE) is sensitive to the shape of the flow profile and is restricted to be used to measure the flow rate of axisymmetric single-phase flows in a circular pipe. In many cases of application, it is not possible to provide a fully developed flow profile. Therefore, the inductive flow sensor has to cope with flow profiles that are not fully developed. To improve the accuracy, an inductive flow sensor with a pair of arc-shaped electrodes flush-mounted on the internal surface of an insulating section of a pipe is proposed in this article to investigate the characteristics of vertical gas-water two-phase flows. The effect of the flow profile on the inductive flow sensor is analyzed. A key contribution of the present work is to estimate the relationship between the induced voltage and the velocity of the conductive phase in two-phase flows. The estimation is achieved by the analytical calculation of magnetic-inductive equations through the method of variables separation. The analytical solution is compared with the results from an ideal model and from numerical simulation. Experiments are conducted to calibrate the inductive flow sensor with arc-shaped electrodes (IFS-AE). It is noted that the proposed IFS-AE can be adopted to obtain the velocity of the conductive phase in two-phase flows by measuring the voltage induced on the arc-shaped electrodes.

1. Introduction

Two-phase flows are characterized by the simultaneous flow along a pipe filled with a combination of two phases which remain separate and can be grouped into four categories: gas-liquid flow, gas-solid flow, liquid-solid flow and liquid-liquid flow [1]. It is of significant importance to study these kinds of flow not only for their scientific interest, but also because they are commonly encountered in many industrial applications. In this work, gas-water two-phase flow with water as the continuous phase in a vertical pipe, which widely exists in the nuclear industry, chemical engineering, air-lift pump and evaporator, is considered. Due to different combinations of flow rates of the two phases, there mainly exist three flow patterns in the vertical gas-water pipe. They are generally categorized into bubbly flow, slug flow and annular flow. The main attention of this article is focused on annular flow, in which the gas phase flows in the center of the pipe and the water phase flows as an annulus around the gas. In addition, gas-water bubbly flow and slug flow are also considered.

One of the most important parameters that characterize two-phase flows is the velocity of separate phases, which is useful to study flow mechanisms, analyze flow structures, identify flow patterns and monitor flow processes. There are many typical methods to measure the velocity, including dynamics method [2], optical method [3], acoustics method [4], thermal method [5], NMR method [6] and cross-correlation method [7]. Among these methods, the cross-correlation technique has been mostly used to obtain the velocity of the dispersed phase in two-phase flows [8]. To estimate the velocity of two-phase flows in which the conductive phase is the continuous phase and no nonconducting phase isolates electrodes from the conductive phase, an inductive flow sensor is much easier and less costly compared with other measuring techniques. This technique is based on the creation of voltage induced across a liquid moving through a magnetic field and has been used successfully to measure the mean velocity of the conductive fluid in single-phase flows for various industries [9]. The main advantage of the inductive flow sensor is its independence of the pressure, temperature, viscosity and conductivity of the fluid. Therefore, continuous efforts have been made to investigate the characteristics of two-phase flows using the inductive flow sensor with spot-shaped electrodes (IFS-SE) [10–13]. The induced voltage is measured between a pair of spot-shaped electrodes. It has been recognized that this kind of flow

---

* Corresponding author. Tel.: +86 15937303264; fax: +86 0373 3326152.
E-mail address: wangmeng@htu.cn (Y.Y. Shi).

http://dx.doi.org/10.1016/j.flowmeasinst.2014.10.019
0955-5986/© 2014 Elsevier Ltd. All rights reserved.

sensor is sensitive to flow profile changes [14]. For this reason, extensive research has been carried out to reduce the inherent sensitivity of the IFS-SE to flow profiles. There are commonly three different approaches to improve the accuracy of the inductive flow sensor, namely shaping the flow profile, manipulating the magnetic field and altering the weight function [15]. However, in order to obtain an axisymmetric flow profile, the flow sensor should be positioned at least 10D downstream and 5D upstream of any flow disturbance, which requires high installation costs for large pipe diameters and is undesired in many cases. The use of an inhomogeneous magnetic field instead of a uniform one generally influences the performance of the flow sensor to axially symmetric profiles [16]. With regard to the method of altering the weight function, an inductive flow sensor with multi-electrode or arc-shaped electrodes can be applied. The inductance flow sensor with multi-electrode is a combination of the IFS-SE and is used to reconstruct the flow profile based on tomographic technique [17]. Considering its large number of electrodes, the inductance flow sensor with multi-electrode is complicated in construction. Compared with the inductance flow sensor with multi-electrode, an inductive flow sensor with arc-shaped electrodes (IFS-AE) has only one pair of electrodes flush-mounted on the internal surface of a nonconductive section of a pipe and is less sensitive to flow profile changes.

This article is aimed to discuss the feasibility of the IFS-AE in estimating the velocity of the conductive phase in gas-water flows. In the following sections, the principle of operation for the IFS-AE is firstly presented for a pipe with a circular cross section. Then the relationship between the induced voltage of the flow sensor and the velocity of the conductive flow is calculated with an analytical method. The results from this analytical method are compared with those from an ideal model and from numerical simulation. Validation is done by a calibration experiment on a laboratory scale, in which only water flows for the single-phase flow and water flows in an annulus between the pipe wall and a centrically mounted acrylic rod for the annular flow.

2. Mathematical model of the inductive flow sensor

The operation of the inductive flow sensor is based upon Faraday's law of induction. Fig. 1 shows the configuration of the IFS-AE. When a conductive fluid passes through a magnetic field, a voltage is generated and detected by a pair of diametrically opposed electrodes mounted on the internal of a circular pipe.

The distribution of the potential U inside the flow pipe is described by a Poisson type equation [18]:

$$\nabla^2 \boldsymbol{U} = \nabla \bullet (\boldsymbol{v} \times \boldsymbol{B}) \tag{1}$$

where $\boldsymbol{v}$ is the velocity vector of the conductive fluid in the pipe and $\boldsymbol{B}$ is the magnetic flux density vector of the exciting magnetic field.

According to Eq. (1), the induced voltage ΔU between the electrodes for the measuring volume τ can be calculated as

$$\Delta \boldsymbol{U} = \int_\tau \boldsymbol{W} \bullet \boldsymbol{v} d\tau \tag{2}$$

where $\boldsymbol{W}$ is weight function vector.

Weight function expresses the contribution of the fluid velocity field of different parts to the output voltage signal and can be written as

$$W = B \times j \tag{3}$$

where $\boldsymbol{j}$ is virtual current density vector which is set up in a stationary liquid by passing unit current density into one electrode and extracting from the other. It is related to the electrodes, the flow sensor boundary and the conductivity distribution within the boundary. In the later analytical study of the IFS-AE, the current excited on the electrodes is set to unity in the computation of the weight function distribution.

Substituting Eq. (3) into Eq. (2), the mathematical model of the inductive flow sensor can be represented as

$$\Delta \boldsymbol{U} = \int_\tau (\boldsymbol{B} \times \boldsymbol{j}) \bullet \boldsymbol{v} \mathrm{d}\tau \tag{4}$$

In consideration of the flow condition and magnetic flux density distribution, Eq. (4) can be expressed as

$$\Delta U = \int_\tau B_y j_x v(r) \mathrm{d}\tau \tag{5}$$

where B_y denotes the constant magnetic flux density in the y-axis direction, j_x is addressed as a component of j in the x-axis direction, $v(r)$ is the uniform rectilinear velocity of the conductive liquid.

As there is no electric source in the measured volume, the virtual current density vector $\boldsymbol{j}$ can be specified by the potential function G as

$$\boldsymbol{j} = \nabla G \tag{6}$$

The potential function G is governed by a Laplace equation as

$$\nabla^2 G = 0 \tag{7}$$

3. Divisionally analytical solution of the IFS-AE

In the following discussion, the relationship between the induced voltage ΔU and the fluid velocity v is investigated for flow distributions with and without an acrylic rod used to simulate the gas phase. To measure the water velocity with the proposed IFS-AE in vertical two-phase flows, each flow pattern must be considered separately because of their differences in flow characteristics. In this article, the main attention is focused on core-annular flow, where the gas flows in the center of the pipe and the water performs as an annulus around the gas. In addition, gas-water bubbly flow and slug flow are also considered. Since

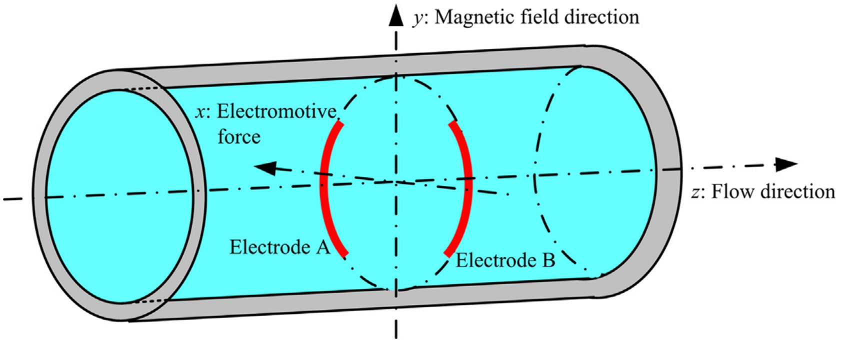

Fig. 1. Configuration of the IFS-AE.