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Original Citation

Leeungculsatien, Teerachai, Lucas, Gary and Zhao, Xin (2009) A numerical approach to determine the magnetic field distribution of an electromagnetic flow meter. In: Proceedings of Computing and Engineering Annual Researchers' Conference 2009: CEARC'09. University of Huddersfield, Huddersfield, pp. 147-152. ISBN 9781862180857

A NUMERICAL APPROACH TO DETERMINE THE MAGNETIC FIELD DISTRIBUTION OF AN ELECTROMAGNETIC FLOW METER

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ABSTRACT

This paper addresses the design of a novel electromagnetic flow meter for use in multiphase flows. The relationship between the magnetic field distribution, the induced electrical potential and the velocity distribution of the conducting continuous phase was studied using COMSOL Multiphysics software (formally known as FEMLAB). The electromagnetic flow meter was modelled to its physical specification i.e. a PTFE pipe located within a Helmholtz coil. The Helmholtz coils were used to produce a magnetic field which was orthogonal to both the flow direction and to a chord joining the detection electrodes. At any instant in time, the magnetic flux density was uniform in the flow cross section. Using the model, the position of the electrodes could be changed to anywhere on the internal surface of the insulating PTFE wall of the flow meter - to satisfy the project requirement of measuring the induced electrical potentials at specific locations on the boundary of the flow.

Keywords Helmholtz coil, Lorentz force

1 INTRODUCTION

In many industries it is important to be able to measure the volumetric flow rates of each of the flowing phases in two phase flows. In the past decade, significant progress has been made in measuring the volumetric flow rate of the dispersed phase in two-phase flows with a conducting continuous phase using electrical resistance tomography (ERT) [1,2]. Very little progress has been made in the development of measurement techniques for measuring the volumetric flow rate of the continuous phase. Based on the theory of electromagnetic induction, electromagnetic flow meters are extensively used in the measurement of volumetric flow of conductive fluid in single phase flows.

The fundamental theory of electromagnetism states that a conductive material moving in a magnetic field experiences Lorentz forces acting in a direction perpendicular both to the motion and to the magnetic field. In 1832 Faraday was the first person to measure the induced voltage across the river Thames by the motion of the water perpendicular to the earth's magnetic field, he placed two large electrodes on either side of the river. The detected signal was imperfect due to electrochemical and thermoelectric effects, these two factors still trouble engineers when they apply the principle of electromagnetic induction to measure fluid velocity. Faraday's experiments mostly failed due to the river bed acting as a short circuit [3].

Long after Faraday's experiment, Williams [5] performed an experiment where a copper sulphate solution passed through a non-conducting circular pipe with a uniform transverse magnetic field acting on the fluid. A Direct current voltage was measured between two electrodes e1-e9 (see figure 1) and this voltage was found to be proportional to the flow rate. From knowledge of fluid mechanics in single phase pipe flows the fluid velocity is not uniform over the cross-section of the pipe and becomes smaller as the pipe wall is approached (boundary layer effect). Accordingly the induced Lorentz forces are not uniform either (see figure 2). Based on the theory of the induction meter the current flow in the fluid is governed by ohm's law in the form

$$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \tag{1}$$

in which $\mathbf{j}$ is the current density vector, σ is the fluid conductivity (scalar), $\mathbf{E}$ is the electric field strength in the stationary coordinate system, $\mathbf{v}$ is the fluid velocity, and $\mathbf{B}$ is the magnetic flux density. The term $\mathbf{v}\times\mathbf{B}$ represents the Lorentz force induced by the fluid motion, while $\mathbf{E}$ is due to charges distributed in and around the fluid and to any variation of the magnetic field in time.

2 NUMERICAL MODELLING OF the ELECTROMAGNETIC FLOW METER

In order to understand the relationship between the magnetic field, induced voltage and the velocity profile of electromagnetic flow meter the magnetic field distribution was simulated with a Helmholtz coil by the use of commercial finite element analysis software knows as COMSOL Multiphysics (formally FEMLAB). COMSOL Multiphysics is a very powerful interactive environment for modelling and solving all kinds of scientific and engineering problems based on partial differential equations (PDEs). The electromagnetic module is an additional package that provides customized dialogue boxes for the physics in sub-domains, boundaries and edges. The problem of electromagnetic analysis on a macroscopic level is that of solving Maxwell's equations subject to certain boundary conditions [4]. In COMSOL, Maxwell's equations are a set of equations written in differential or integral form, conditioning the relationship between the fundamental electromagnetic quantities. According to Ohm's law stated in equation (1), an electromagnetic flow meter can be investigated using the COMSOL 'Electric and Induction Currents' application mode and time-harmonic stationary linear solver (contained in the COMSOL 'AC/DC' module) to solve for the magnetic field distribution and the induced potentials.

2.1 Numerical Modeling of the Helmholtz Coil

A Helmholtz coil consists of two identical circular coils. In an electromagnetic flow meter these are placed symmetrically on each side of the PTFE (polytetrafluoroethylene) flow pipe (figure 3). The coils are wound such that the current flow through both coils is in the same direction and each coil carries an equal amount of electric current. For a DC current this would result in an approximately uniform magnetic flux density distribution between the coils. The approximate uniformity of the magnetic field is the result of the sum of the field components of the two coils parallel to axis of the coils (the y-direction in figure 3 (a)). Setting the coil radius R equal to the coil separation L (where L is the outer diameter of the PTFE pipe) minimizes the non-uniformity of the field at the pipe centre (see figure 3). Simulations were carried out to investigate the uniformity of the magnetic flux density in the pipe cross section generated by the Helmholtz coils.

The magnitude B_m of the magnetic flux density generated by Helmholtz coil at the midpoint of the two coils is

$$B_m = \left(\frac{4}{5}\right)^{3/2} \times \frac{\mu N I}{R} \tag{2}$$

where N is the number of turns in each coil, I is the current flowing through each coils in ampere, R is the radius of the coils is meter, and μ is the permeability constant ($\mu = 4\pi\times10^{-7}$ Hm^{-1}).

2.1.1 Physical Specification of the Electromagnetic Flow Meter

The electromagnetic flow meter model was assumed to be made from a PTFE flow pipe and two circular identical copper excitation coils (the Helmholtz coil). The inner diameter of the flow pipe is

0.08m, the outer diameter is 0.09m and the length of the flow pipe is 0.3 m. The inner and outer diameters of the two-excitation coils are 0.2048m and 0.2550m respectively. A cylindrical domain with a diameter of 0.32m and a length of 0.32m represents the boundary of the computing domain [6, 7]. Figure 4(b), 4(c), and 4(d) present views of the $y-z$ plane, $x-y$ plane and $x-z$ plane respectively, whilst figure 4 (a) is a three-dimensional representation of the electromagnetic flow meter system geometry.

2.1.2 Physical settings

An external ac excitation current is imposed in the coils to generate an ac magnetic field, the ac source frequency is 50 Hz. The magnetic vector potential $\mathbf{A}$ must satisfy the following equation:

$$\mathbf{j}\omega\sigma\mathbf{A} + \nabla\times\left(\mu^{-1}\nabla\times\mathbf{A}\right) = \mathbf{J^e} \tag{3}$$

in which ω is the angular frequency, σ is the conductivity, μ is the permeability and $\mathbf{J^e}$ is the external current density applied. The relationship between the magnetic vector potential $\mathbf{A}$ and the magnetic flux density B is given by

$$\mathbf{B} = \nabla\times\mathbf{A} \tag{4}$$

The model uses the permeability of the vacuum, that is, $\mu = 4\pi\times10^{-7}$ Hm^{-1}. The external current density is zero except in the coils. The external current source density applied to each excitation coil is:

$$\mathbf{J^e} = -\frac{zJ_0}{\sqrt{x^2+z^2}}\mathbf{i} + 0\mathbf{j} + \frac{xJ_0}{\sqrt{x^2+z^2}}\mathbf{k} \tag{5}$$

In which J_0 is a constant current applied with its initial value of 3.32×10^7 A. The flow pipe is assumed to be made of PTFE with conductivity σ of 1×10^{-15} Sm^{-1}.

3 NUMERICAL SIMULATION RESULTS

According to the geometrical model, physical model, physical setting, and the preconditions explained in sections 2.1.1 and 2.1.2, the distribution of magnetic flux density $\mathbf{B}$ on the $x-y$, $x-z$, and $y-z$ planes are shown in figure 4. Figure 4 (a) shows the magnetic field distribution on the $x-y$ plane (z=0), the arrows indicate the magnitude and direction of the magnetic flux density. The color scale shows the magnitude of the magnetic flux density. The maximum magnitude of the magnetic flux density is 1.641e^{-3} T and the minimum magnitude is -1.483e^{-3} T. Figure 4 (b) on the $x-z$ plane (y=0) shows the maximum magnitude of the magnetic flux density is 4.953e^{-4} T and the minimum magnitude is -5.099e^{-4} T. Figure 4 (c) on $y-z$ plane (x=0) shows the maximum magnitude of the magnetic flux density is 1.593e^{-3}T and the minimum magnitude is -1.304e^{-3} T. It is clear that the magnetic flux density distribution is not uniform between the coils and that the magnetic field vector is not parallel to the y axis at locations close to the coils. However we are only interested in the magnetic field distribution within the flow cross section shown in figure 4 (d), which indicates that the magnitude of the y component of magnetic flux density has a minimum of 7.757e^{-4} T and a maximum of 8.044e^{-4} T. Another point that needs to be made is that the magnitude of the y component of the magnetic flux density. In figure 4(d) would be expected to be symmetrical about x = 0. The slight asymmetry shown is due to numerical errors in the COMSOL simulation. Nevertheless, this is extremely insignificant compared to a variation of the magnetic field distribution outside the flow pipe. Therefore the magnetic field distribution could be assumed uniform in the flow cross section. The mean value of the y

component of magnetic flux density $\mathbf{B}$ in the flow cross section is 7.996e^{-3} T (7.996 Gauss) according to figure 4 (d).

4 CONCLUSIONS AND FURTHER WORK

Based on the physical geometry of the electromagnetic flow meter, electrodes could be placed on the internal circumference of the pipe where z is zero. This is where the magnetic flux density is understood to be exceptionally uniform.

The research described in this paper can be further extended to numerically simulate the weight function distribution in the flow cross section for any arbitrary electrode locations situated on the internal circumference of the flow pipe. Then the weight functions could be used to reconstruct the velocity profile by making potential difference measurements from arrays of electrodes mounted around the internal circumference of the flow pipe. This will enable measurements in highly non-uniform single phase velocity profiles and also measurement of the velocity profile of the conducting continuous phase in multiphase flows. Numerical simulation would provide design parameters for such a tomographic instrument and would also assist in the development of the relevant reconstruction algorithms.

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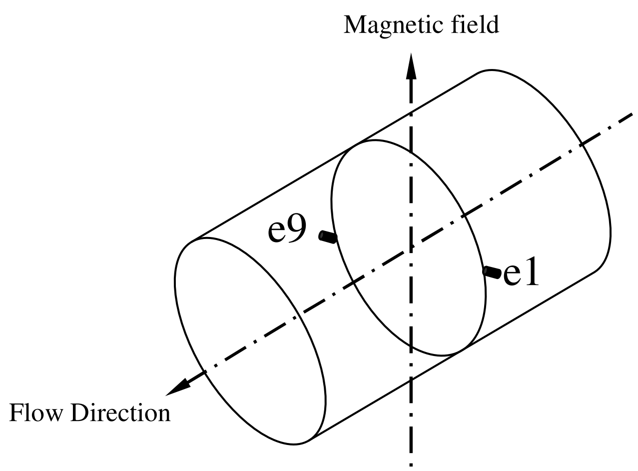


Figure: 1 Transverse-field flow meter

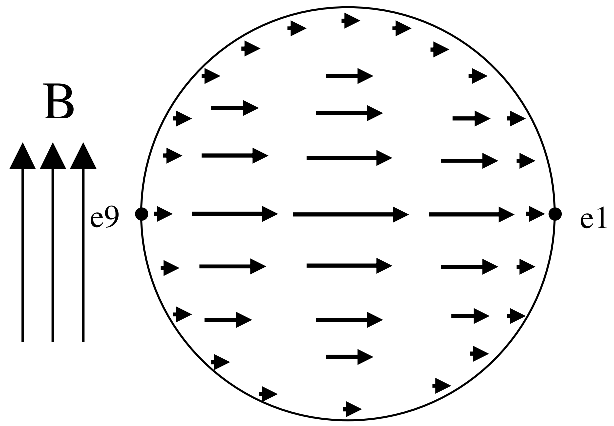
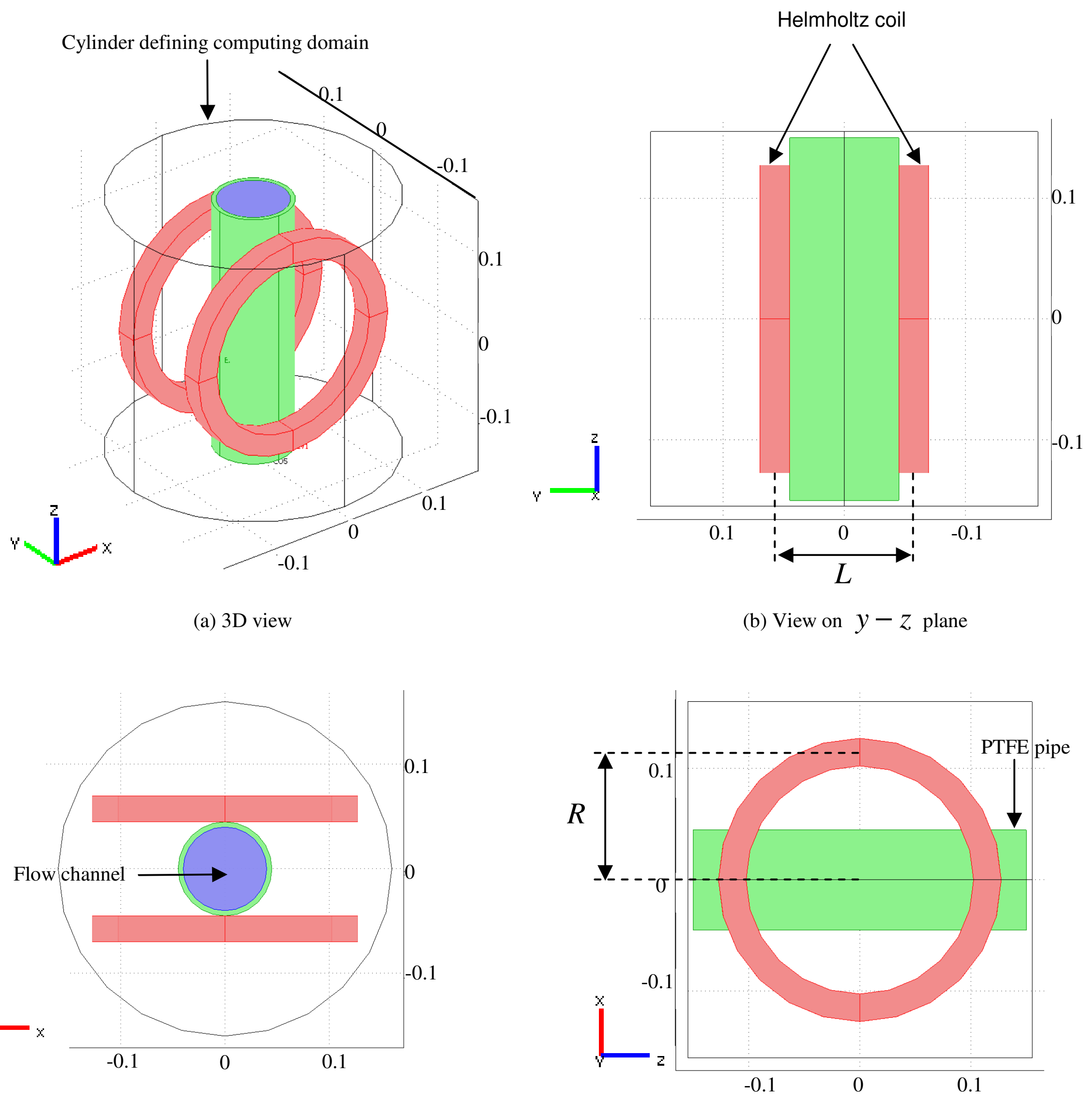


Figure: 2 Lorentz forces



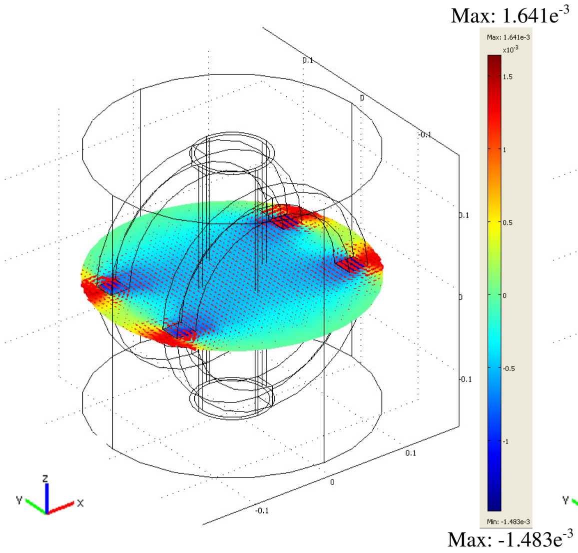
(a) 3D view

(b) View on $y-z$ plane

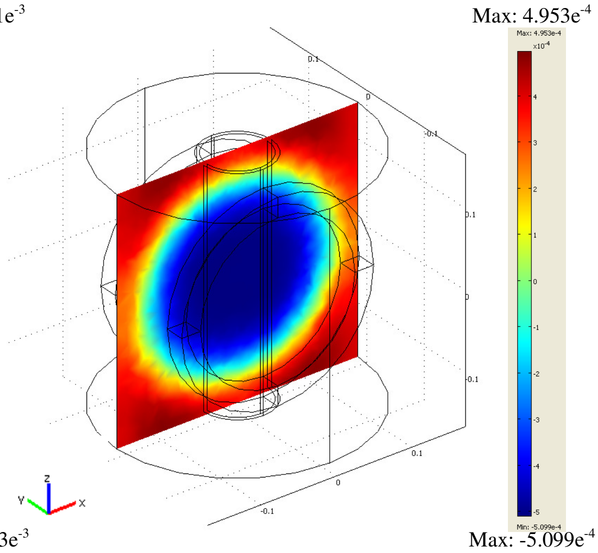
(c) View on $x-y$ plane

(d) View on $x-z$ plane

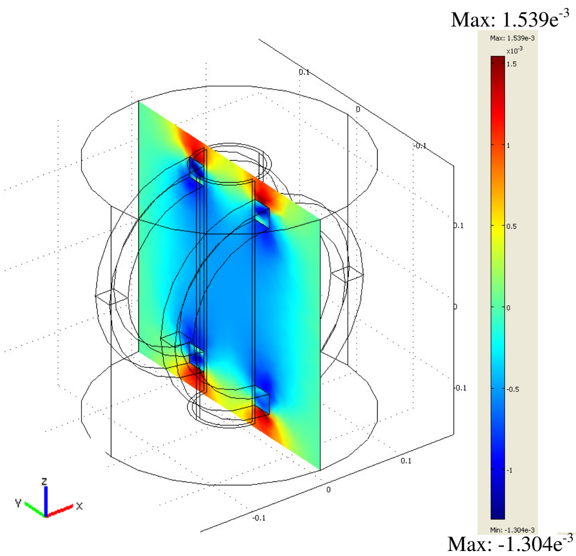
Figure 3: Geometrical model and coordinate system of the flow meter



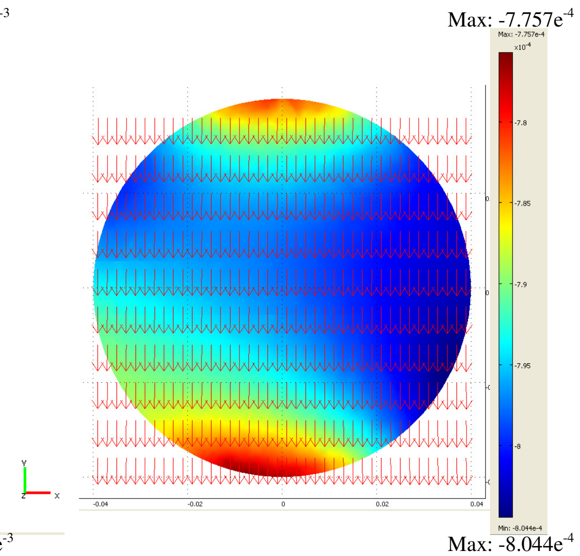
(a) y component of the magnetic flux density (T) on $x-y$ plane



(b) y component of the magnetic flux density (T) on $x-z$ plane



(c) y component of the magnetic flux density (T) on $y-z$ plane



(d) y component of the magnetic flux density (T) on $x-y$ plane. The arrows represent magnitude and direction of combined x and y components of the magnetic flux density in the in the $x-y$ plane

Figure 4: Magnetic flux density distribution of electromagnetic flow meter