Finite Element Analysis to investigate electromagnetic flowmeters of diverse cross-sectional shapes

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Abstract:
The electromagnetic (EM) flow meter works on the principle of EMF (Electromotive Force), induced in a moving liquid under the influence of a magnetic field. Owing to their accuracy and non-invasiveness, EM flow meters are attractive flow sensing devices used across industries like power generation, oil and gas and food processing. While currently design flowmeters fully meet customer expectations, it is always desirable to further improve performance of the meters. This study employs finite element (F.E.) based multiphysics modeling to investigate possible improvement in flowmeter performance, by varying the cross sectional shape and evaluating the outcome against that of the traditional circular cross sectional flowmeters.

Keywords: Finite Element, Magnetic Flow meter, Induced EMF, Cross sectional shape

1. Introduction

EM flowmeters work on the principle of Faraday's law of electromagnetic induction. In short when an ionic fluid like ordinary water flows across a magnetic field an EMF proportional to the velocity is induced across the cross section. The EMF given by Φ1-Φ2 (potential difference), and divided by the average velocity gives sensitivity of the flow meter. Pioneering work in EM flowmeter research was performed by Shercliff [1], who used analytical calculations to provide an understanding into the intricacies of flowmeter operation. Since his work, there have been significant strides in finite element (F.E.) calculation methods in 3 dimensions. This study uses COMSOL Multiphysics [2] to develop a F.E. model of the EM flowmeter. The model is used to investigate an important aspect of flowmeter design, the pipe cross sectional shape.

High sensitivity or signal strength of the flowmeter is one of the primary performance criteria, since high sensitivities can overcome the possibility of adulteration of the useful signal by stray noise signals. Signal strength primarily depends on the magnetic field strength which in turn depends on the current powering the coils and the number of turns in the coils. It is however desirable to obtain high signal strength using the same magnetic field strength, by other design modifications. A less discussed aspect of electromagnetic flowmeters is the effect of cross sectional area on signal strength. The focus of this study is to investigate the effect of various pipe cross sectional shapes on flowmeter sensitivity. Extensive use of COMSOL multiphysics [2] was made, leading to valuable conclusions on the effect of pipe cross sectional shape on flowmeter performance.

2. Use of COMSOL Multiphysics

The computational domain or geometry to simulate EM flowmeter performance is shown in figure 1A. A simplistic model not representative of commercial flowmeters was used. The model comprises an insulated pipe, with electromagnetic coils (which generates the magnetic field) above and below the pipe. An air domain is provided around the pipe and coils, in order to simulate the real environment. Figure 1B, shows the mesh or discretization of the computational domain. The mesh employed tetrahedral elements and was adequately refined. Boundary layers were provided at the pipe walls to accurately capture turbulent flow physics.

The modules of magnetic and electric fields and fluid flow were invoked, to solve the electromagnetism and fluid dynamics physics within the domain. In short the magnetic and electric field module solved magnetic propagation and the fluid flow module solved fluid flow through the pipe. Subsequently, the Lorentz force term was used to evaluate the interaction between the magnetic flux density and fluid velocity, to yield the induced electric potential (which is proportional to the velocity).

In reality the induced potential is measured by electrodes (not shown in Fig 1A) to estimate the fluid velocity.

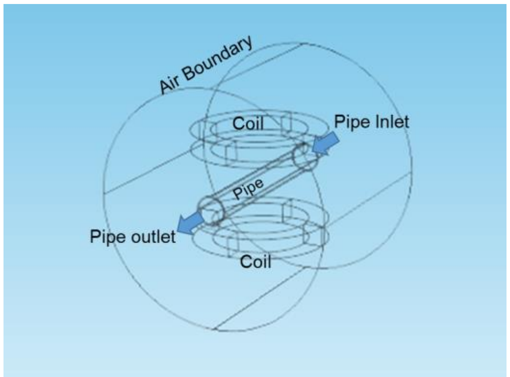

Fig 1A

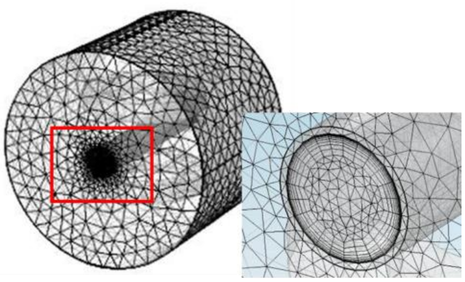

Fig 1B

Figure 1A: Geometry of EM flowmeter model (circular cross section) used in calculations; 1B: Discretization of geometry showing boundary layers on pipe wall.

2.1 Governing Equations

The fluid flow module simulated fluid flow through the pipe using the mass (eq. 1) and momentum conservation (eq. 2) equations:

$$\nabla . u = 0 \quad 1.$$

$$\rho u \nabla u = -\nabla p + \mu \nabla^2 u + F \quad 2.$$

Where, u is velocity vector, p is pressure, ρ is density and μ is dynamic viscosity. Equations 1 and 2 above, depict laminar flow, for simplicity. In reality turbulent version of the momentum conservation was solved using the RANS (Reynolds average navier stokes equation) method. The electric and magnetic field module first calculated the magnetic field generated by the circular coils each on either side of the pipe. A DC current was supplied to both the coils in the same direction, and the magnetic field, B(x,y,z) within the pipe was calculated using the Ampere's law.

$$\nabla \times \mu_0^{-1} \mu_r^{-1} B = J \quad 3.$$

The Electric field induced in the fluid was calculated using the Lorentz force term.

$$J_i = \sigma E + \sigma u \times B \quad 4.$$

Where E is the induced electric field generated by the fluid-magnetic field interaction, u×B (Faraday's law). J is the current induced internally in the fluid and σ is fluid electrical conductivity. Velocity, u, was obtained from the fluid flow equations, 1 and 2. Electric potential difference, or EMF, induced within the fluid was found by integrating equation (4) over the fluid domain. Hence using COMSOL Multiphysics, EMF induced by the interaction of flow and magnetic fields was computed.

2.2 Boundary and Initial Conditions

For the fluid flow calculations, a uniform inlet velocity was imposed across the pipe inlet and ambient pressure was imposed at the outlet. No slip boundary condition (u = 0) was imposed at the pipe walls. The pipe and coils were enclosed in an air domain (Fig 1A). A magnetically insulated boundary condition was imposed at the wall of the air domain. The pipe wall was considered electrically insulated.

2.3 Computational Method

The magnetic field induced by the powered coils was simulated using the "Multi-turn Coil" option specifying the coil type as being "circular" which requires the current loop to be specified. A stationary or steady state analysis was performed using the segregated solver for the fluid flow equations. The AMS (Auxiliary Maxwell Solver) was used to solve the electromagnetic equations.

2.4 Test cases

Three different pipe cross sectional shapes were investigated as shown in figure 2: circular, rectangular and triangular. Due to space constraints the width of each cross section was kept constant. The area of cross section for every shape was maintained constant by adjusting the height. Area of cross section was maintained constant so as not to incur an additional pressure drop (smaller areas result in increasing pressure drop, which is undesirable).

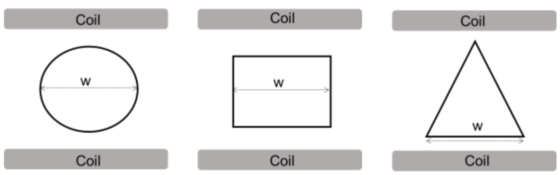

Figure 2: Circular, rectangular and triangular pipe cross section of pipe, of same width and cross sectional area.

3. Results

Figure 3 depicts results of simulating the flowmeter with circular cross sectional shape. Figure 3A shows velocity contours across various sections across the pipe. Figure 3B shows magnetic flux distribution across the domain. As expected the density is highest at the central zone, covering the entire pipe cross section. Figure 3C, shows the induced electric potential across the pipe cross section. Not shown in the figure, the electric potential at the extreme ends, Φ1 and Φ2, are measured by electrodes in reality. The difference between the two is the induced EMF, which is divided by the area averaged velocity to give sensitivity of the flowmeter under analysis.

Figure 4 shows magnetic flux distribution across the circular, rectangular and triangular cross sections of the pipes. Figure 5 shows the sensitivity obtained from the three pipes, normalized with that given by the circular pipe. There is a marginal improvement in sensitivity of the rectangular pipe flowmeter compared to that of the circular shaped flowmeter. It is seen that the triangular pipe flowmeter has the highest sensitivity than the others. In order to explain this, we refer back to figure 4. It is seen in figure 4, that the triangular pipe spans a significant zone of the gap between the coils in the vertical direction. In other words, the triangular pipe is closer to the top and bottom coils where magnetic flux is significantly high. Hence the triangular pipe flowmeter yields the highest sensitivity.

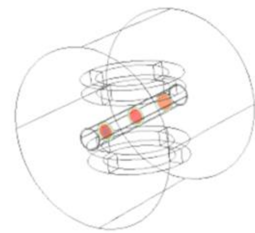

Fig 3A

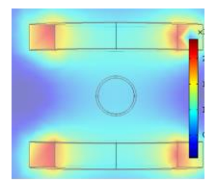

Fig 3B

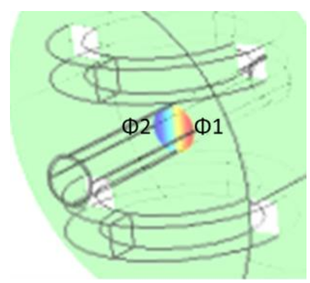

Fig 3C

Figure 3A: Velocity contours across pipe sections; 3B: Magnetic flux distribution across central pipe section; 3C: Induced electric potential across central pipe section. Φ1 and Φ2 are potentials at extreme ends for detection.

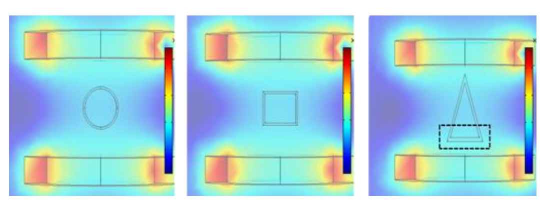

Figure 4: Magnetic flux distribution across central pipe section for the circular, square and triangular cross-section flowmeters.

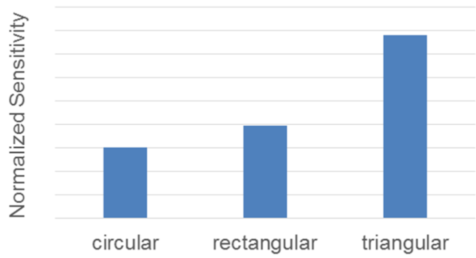

Figure 5: Normalized sensitivity obtained from circular, rectangular and triangular cross section flowmeters.

4. Conclusion

The study concludes that under the given set of conditions and constraints, triangular shaped flowmeters yield the highest sensitivity or signal strength. This study was based on a single velocity, and can be extended to other fluid velocities as well. This way a more comprehensive picture of the investigation can be obtained. The multiphysics model is a platform to evaluate design modifications of the flowmeter and is not only limited to studying the effect of cross sectional shapes. The model can be used for other useful parametric studies as well.

5. References

[1] Shercliff J.A., 1987. The Theory of Electromagnetic Flow Measurement, Cambridge University Press, pp. 10-47.
[2] COMSOL Multiphysics Ltd. Version 5.1. Burlington. MA.