Electromagnetic Flow Meters

The electromagnetic flow meter (Shercliff 1962) is a very convenient, robust and simple device with which to measure the total, integrated volume flow rate in a pipe provided the fluid has some minimal electrical conductivity. A sketch of the basic components is shown in Figure 1. Magnets or electrical coils are arranged outside the pipe so as to produce a uniform magnetic field of magnetic flux density, $\underline{B}$, perpendicular to the axis of the pipe and perpendicular to the direction of the flow (we address the issues raised by non-uniformity of the magnetic field once the basic principle of the device has been established. Then, since the

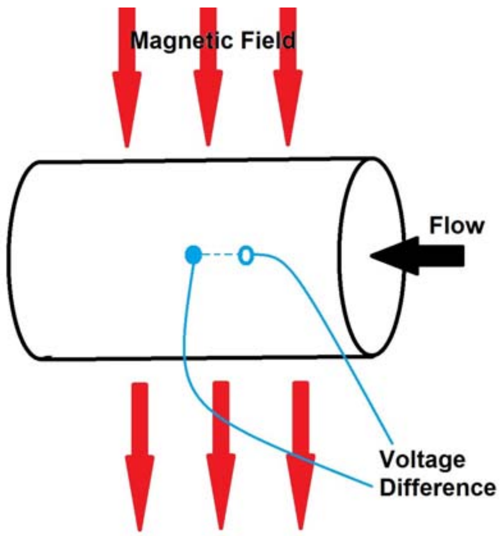

Figure 1: The Electromagnetic Flow Meter.

flow of the fluid represents an electric current in the axial direction and the magnetic field is perpendicular to that direction, by basic electromagnetic principles this produces an electric potential gradient in the third perpendicular direction whose magnitude is proportional to the current and to the magnetic flux density. Thus, by measuring the electric potential voltage difference between two points at the ends of a diameter in that third perpendicular direction, one can acquire a signal that is proportional to the current or flow rate. We will proceed to analyze some of the detailed physics of the electromagnetic flow meter; the reader is referred for more details to Shercliff's classic book (Shercliff 1962) on the subject of electromagnetic flow meters.

As depicted in Figure 2 we analyze the electromagnetic conditions in a cross-sectional plane of the pipe assuming a uniform magnetic flux density, $\underline{B}$, in the x direction. The velocity, $v(x,y)$, of the flow is assumed to be perpendicular to the sketch in Figure 2 but may vary over that cross-section. We also denote by $\underline{E}(x,y)$, the electric field generated by the combination of the magnetic field, $\underline{B}$, and the current associated with the flow. Then the electric potential, $\mathcal{U}$, of the electric field is given by

$$\underline{E} \ = \ -\nabla\mathcal{U} \tag{Kdcc1}$$

and the electric current vector, $\underline{j}(x,y)$, this causes is then given by Ohm's law as

$$\frac{\underline{j}}{\sigma} \ = \ -\nabla\mathcal{U} + \underline{v}\times\underline{B} \ = \ \underline{E} + \underline{v}\times\underline{B} \tag{Kdcc2}$$

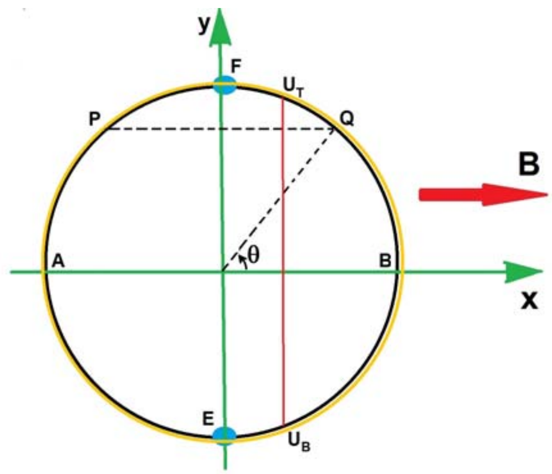

Figure 2: Theory of the Electromagnetic Flow Meter.

where σ is the electrical conductivity of the flowing fluid. We will be primarily interested in the component, j_y, of $\underline{j}$ in the y direction which is therefore given by

$$\frac{j_y}{\sigma} = -\frac{\partial \mathcal{U}}{\partial y} + Bv \qquad \text{(Kdcc3)}$$

where B denotes the magnitude of the uniform and constant magnetic flux density in the x direction and $v(x,y)$ the fluid velocity which could vary over the cross-section. We note at this point that we will assume that the induced electric currents are sufficiently small so that the induced magnetic field can be neglected. If this is not the case the analysis is a little more complex; this is needed when the electric currents are larger as they are with liquid metals (see Shercliff 1962).

The last step in the derivation is to integrate equation (Kdcc3) over the cross-section area enclosed by the pipe walls. Since the pipe walls are electrically insulated (an additional design constraint) it follows that the total induced electric current across a line such as PQ in Figure 2 is the same at all y positions. Denoting this by J it follows that

$$\int_P^Q j_y \, dx = J \qquad \text{(Kdcc4)}$$

and

$$\int_{y=-R}^{y=R} \int j_y \, dx \, dy = 2RJ \qquad \text{(Kdcc5)}$$

where R is the internal radius of the pipe. Consequently integrating equation (Kdcc3) over the entire cross-section and assuming B is uniform, yields

$$B \int \int v \, dx \, dy = BQ = \int \int \frac{\partial \mathcal{U}}{\partial y} \, dx \, dy + \frac{2RJ}{\sigma} \qquad \text{(Kdcc6)}$$

where Q is the total volume flow rate in the pipe irrespective of the distribution of the velocity. Moreover, the first term on the right hand side can be integrated so that equation (Kdcc6) may be written as

$$BQ = \int (\mathcal{U}_T - \mathcal{U}_B) \, dx + \frac{2RJ}{\sigma} \qquad \text{(Kdcc7)}$$

where $\mathcal{U}_T$ and $\mathcal{U}_B$ are the electric potentials at the ends of a line such as shown in Figure 2. Then, if the the velocity distribution is axisymmetric it necessarily follows that the potential $\mathcal{U}$ on the pipe surface will vary like $\mathcal{U}^* \sin\theta$ (where θ is the angle shown in Figure 2), that the integral in equation (Kdcc7) is equal to $\pi R\mathcal{U}^*$ and the the electric potential difference between the electrodes E and F is $2\mathcal{U}^*$. Therefore

$$BQ = \pi R\mathcal{U}^* + \frac{2RJ}{\sigma} \tag{Kdcc8}$$

and the volume-averaged fluid velocity, $\overline{v} = Q/\pi R^2$, is given by

$$\overline{v} = \frac{1}{BR}\left\{\mathcal{U}^* + \frac{2J}{\pi\sigma}\right\} \tag{Kdcc9}$$

In many meters the induced electric current, J, is so small that the second term in the brackets can be neglected and the sensitivity of the electromagnetic meter is given by

$$\overline{v} = \frac{\mathcal{U}^*}{BR} \tag{Kdcc10}$$

Note that the sensitivity of the meter is then independent of the electrical conductivity of the fluid. Therefore, in theory, the meter could be used irrespective of the electrical conductivity of the fluid provided the voltage difference, V, can be measured. However, in practice, one can only measure that voltage difference, V, by drawing a certain electric current from the electrodes which requires a small, non-negligible electrical conductivity. In practice, this requires a device to measure the voltage difference whose internal electrical impedance is much larger than the electrical impedance of the fluid between the electrodes. This is difficult to achieve in some fluids, such as cryogenic liquids.

Though we have focussed above on a simple cylindrical geometry, electromagnetic flowmeters come in a vast range of shapes and sizes. Some are intended for accurate flow rate measurement, but some are intended only for the detection of flow. This is particularly the case for some of the very first electromagnetic flowmeters which were devised to allow detection of the resumption of blood flow after surgery in which the flow was interrupted or in which the object was to regenerate flow. EM flowmeters are sold in sizes ranging from millimeter diameters to meter diameters. Many of the smaller versions use permanent magnets and therefore DC fields though their performance in aqueous fluids may be degraded by ionization at the electrodes. Many larger versions use large coils with magnetic cores to generate AC magnetic fields that avoid the ionization problems. Though these usually function with line frequencies ($60Hz$) the author adapted several to be driven at much higher frequencies (about $500Hz$) so as to measure oscillating flow rates at frequencies up to about $50Hz$; such measurements are almost impossible to make with any other device due to the complicated velocity profiles that occur at these frequencies.