Recent progress in magnetic-inductive flow metering devices (MID)

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Abstract— **Flow sensors for the measurement of volume or mass flow rates of gaseous or liquid media are good examples of ubiquitous sensors. They are to be found not only in almost any industrial process but rather in any process at all, where material and/or energy flow rates play a role. In most of the application fields aqueous media have to be measured. For volume flow measurement the magnetic-inductive principle has distinct advantages, since it allows for smooth inner walls without any obstacles or dead space. It doesn't depend on the temperature, pressure, viscosity of the flow medium. Interestingly it doesn't even depend on the flow profile. It however requires a minimum conductivity of about 5 µS/cm. Fortunately the majority of the aqueous fluids meet this requirement so that the magnetic-inductive principle has a big market potential. Only recently it has been shown that contrary to the existing systems which apply time dependent fields in order to cope with the error signals caused by electrochemical fluctuations of the solid-fluid interface double layer potentials, now systems working with a time constant magnetic field come into reach. Their additional advantages are manifold: Application of modern rare earth permanent magnets allows for fields two orders of magnitude above that of existing devices with a correspondingly higher resolution, for continuous in contrast to discrete measurement and for zero energy. All these arguments in combination with an easy construction make permanent magnet driven flow sensors ideal candidates in ambient intelligence systems.**

Keywords- magnetic-inductive flow sensor; permanent magnet; continuous flow; pulse; metal oxide; double layer potential.

I. INTRODUCTION, PRINCIPLES OF MID-OPERATION

The following Fig.1 illustrates the principal operation of a magnetic-inductive flow sensor. The medium flowing with the velocity v through the flow tube with the circular cross section of diameter d interacts with the magnetic field with the flux density B generated by magnets M to result in the magnetic-inductive voltage U0 arising perpendicularly to both the flow velocity and the magnetic field lines. This voltage will be coupled to the outside through the coupling units CU1, CU2 for further treatment in the signal evaluation unit SE. The signal path includes the double layer voltages UD1 and UD2 on the surfaces of the upper and lower coupling units. These voltages will occur at every solid-fluid interface. The double layer is well known as the Helmholtz layer in electrochemistry.

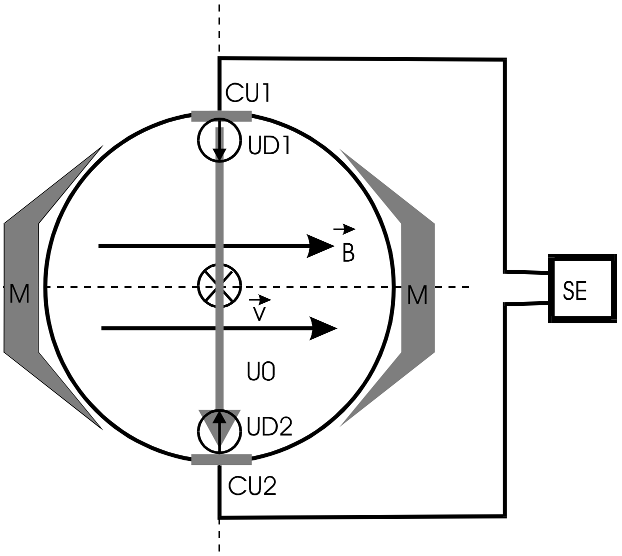

Figure 1. MID principal arrangement

Then the resulting voltage coupled to the outside may be described by

$$U = U0 + UD1 - UD2 = U0 + \Delta UD , \tag{1}$$

with U0 given by

$$U0 = B \cdot d \cdot v . \tag{2}$$

Usually the double layer voltages at the two interfaces differ from each other so that their difference remains as an error signal superimposed to the useful signal. It may be eliminated only by at least two consecutive measurements at different magnetic field amplitudes. Then, assuming the difference of double layer voltages to stay constant the difference in total voltage between these two measurements results in the elimination of the error signal.

In the existing devices the time dependent magnetic field will be supplied by field coils excited by a pulse current with a corresponding pulse field of amplitude B. The signal difference taken from samples during the pulse, Ub, and at zero field level, Uzero, directly leads to the useful magnetic-inductive Voltage U0:

$$Ub - Uzero = \left(U0 + \Delta UD\right) - (\Delta UD) = U0\,, \quad (3)$$

as long as the difference of double layer potentials ΔUD remains constant.

II. CHARACTERISTICS OF THE TIME DEPENDENT OPERATION OF MIDS

The time dependent operation has a number of drawbacks: Due to the current flowing at least the Ohmic losses in the field coil have to be supplied by external means. These losses principally have to be kept low for low energy consumption and correspondingly limiting the inner temperature of the sensor. In the pulsed mode the average power losses P are proportional to the square of the pulse amplitude of the current and - due the linearity between current and magnetic field - of the flux density B and to the duty factor τ/T where τ is the pulse width and T is the period length [1],

$$P \propto I^2 \frac{\tau}{T} \propto B^2 \frac{\tau}{T}, \quad (4)$$

so that for a given power P allowed from cooling conditions the flux density allowed becomes

$$B \propto \sqrt{\frac{T}{\tau}} \cdot \sqrt{P}\,. \quad (5)$$

In practice among other arguments the period length T will be chosen by such considerations as the typical time constant of the flow rate to be measured, and the inverse of the typical highest frequency of the double layer signal and other disturbing signal components, which corresponds to the typical period length of the disturbing signals. In fact the pulse period length to be selected has to be small against the smaller of these both. Due to the square root function in (1) there is a rather poor gain in the flux density with the right hand side parameters. E,g. doubling the power P at constant duty factor τ/T will result in a 40 % gain only in B. Similarly doubling the period length T at constant power P would lead to the same result.

Since for an existing layout of an MID the allowed power consumption P may be considered as given and the pulse period T has to be chosen according to the above rule, there is no design freedom left, when further taking into account that the pulse length τ has a lower limit regarding the time necessary to establish stable measuring conditions after switching the pulse.

The only way to overcome these limitations will exist in taking direct influence on the time behaviour of the error signal. The goal must be to keep its frequencies below those of the flow signal. As will be shown below this is feasible. It leads the way to avoid time dependent fields at all and to replace the field coils by permanent magnets.

Summarizing we may state that current generated time dependent magnetic fields put severe limitations on the function of MIDs among which the non continuous mode of operation, their lack in resolution capabilities and the power requirements are the most important ones.

III. THE MID FOR CONTINUOUS FLOW MEASUREMENT

The most demanding flow measurement tasks require high resolution and continuous operation. As has been pointed out above both are not possible with contemporary MIDs. The only way is to use a constant magnetic field which in the most straightforward way will be realized by modern permanent magnets. Besides the advantages to be discussed in the following they allow an unparalleled ease of design.

Due to their extraordinarily high fields rare earth permanent magnets such as e.g. Samarium Cobalt (SmCo) and Iron Neodymium (NdFe) will be the right choice. We have shown that with these magnets flux densities of 0.5 Tesla may be achieved inside a flow tube of 10 mm width, which is by almost a factor of 2 orders of magnitude above those of current driven devices. Due to the proportionality according to (2) the same factor applies to the resolution capabilities and to the signal to noise ratio to be expected from permanent magnet driven devices.

However the problem of error signals introduced by electrochemical phenomena needs careful consideration. As we mentioned above on every solid-fluid interface a double layer potential will build up due to the action of surface charges in the form of electrons or ions. The double layer is well known as Helmholtz double layer in electrochemistry. The double layer potential is therefore called Helmholtz-potential. It is the result of a thermal equilibrium in which the numbers of charges entering and leaving the surface are equal.

For metal surfaces the detailed processes are especially complex, since neutral atoms from the surface go into solution in form of the corresponding ions and vice versa so that every current flow is accompanied by a material flow. The charge transfer from ionic to electronic conduction in both directions is a very complex process and is accompanied by a number of impeding sub-processes, each of them being responsible for a characteristic over-voltage as a function of the current amplitude. Some of these processes depend on an energy barrier (activation energy) which has to be overcome Examples are the charge transfer over-voltage, the crystallization over-voltage and the diffusion over-voltage. Even for noble electrodes these considerations are valid although the electrode material doesn't go into solution. Most of these charge transfer processes occur within the Helmholtz double layer and they are additionally impeded by the so called hydratation where ions are surrounded by a mantle of water molecules which is the reason for an energy barrier.

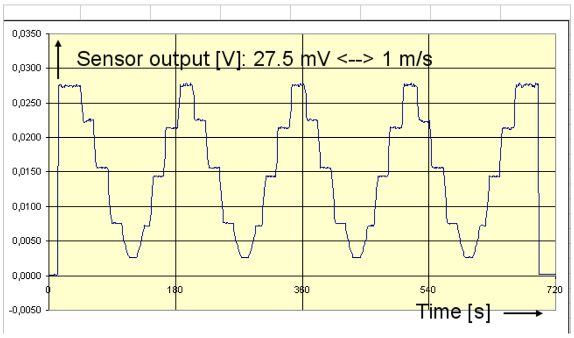

Figure 2. Record of periodic flow with permanent magnet MID

Summarizing electrodes showing the behaviour just described as over-voltage and activation energy are called polarized electrodes. Due to the many processes involved they show an often erratic time dependence of the Helmholtz double layer potential. The difference ΔDU = UD1 – UD2 (see Fig. 1) of two of these potentials will show the same erratic behaviour. This is true for all metallic electrodes as coupling units. Therefore metallic coupling units are not well adapted to be used in constant field MIDs.

The above discussion for metal electrodes however leads the way to a solution which is to be found in a proper surface of the coupling units CU1, CU2. From modern electro-medical systems [2] it is known that special coatings lead to the desired non erratic behaviour of the double layer potential. In fact they don't show any of the adverse effects from above which is ascribed to their functioning as ion buffers.

It is this property that led to the suggestion [3] of oxide ceramic surfaces as signal coupling interfaces. In [4] especially the oxide-electrolyte interface with SiO2 as the oxide has been intensively studied. The hydroxyl groups SiOH there may accept or donate protons from the medium thus behaving as an H^+-ion buffer. Then the double layer potential solely depends on the H^+-concentration of the medium or on its pH-value.

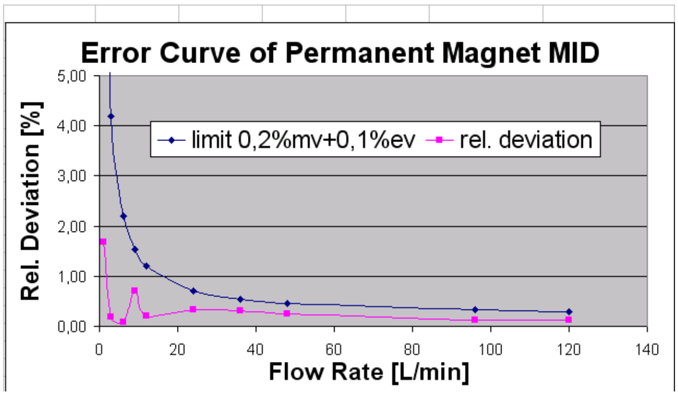

Figure 3. Error curve of permanent magnet MID

This is an extremely important result for the practical realization of constant magnetic field MIDs: The double layer voltage will not depend on the intricacies of the material of the solid coupling unit any more but rather on the properties of the fluid medium, in this case its pH-value. Since both coupling units CU1, CU2 see the same fluid properties they will show the same potentials, which in the difference UD1-UD2 cancel out.

In the meantime we have experimental evidence for this behaviour. As an example Fig. 2 shows the record of a periodically varying fluid flow over a total time period of 720 seconds with minimum signal drift and almost no noise. Note that the record is really continuous and will follow arbitrarily rapid flow changes. The plot shows the high reproducibility and extremely high resolution represented by a signal of 27.5 mV corresponding to a flow velocity of 1 m/s.

In Fig. 3 a plot of the error characteristic of a permanent magnet MID is given together with the error limits of 0,2 % with respect to the actual measured value plus 0,1 % from the end value, which are typical for high quality MIDs.

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