In-line viscometry by using a modified electromagnetic flowmeter

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INTRODUCTION

Continuous viscosity measurement assists in product quality procurement and maximizes the efficiency of plant operation. However, state-of-the-art commercial process instruments have severe drawbacks such as using by-pass loops or being invasive [1,2].

A main difficulty of acquiring the viscosity is the active interaction between the sensor and the material being processed. The material must be subjected to a controlled deformation while monitoring the resulting stress. Our approach to the problem is to use the mechanical interaction of the pipe flow itself. The flow velocity profile is acquired by a non-invasive measurement and the rheological properties are determined proximately. So, the viscosity is obtained directly in the process line for Newtonian as well as non-Newtonian fluids.

MEASURING PRINCIPLE

An electromagnetic flowmeter is a widely used non-invasive sensor for flow measurement of electrically conducting fluids. A coil system mounted on the outside of the pipe generates a homogeneous magnetic field perpendicular to the pipe axis (see Fig. 1a). The voltage $U_0$ induced between two electrodes mounted at an electrically insulated pipe wall is proportional to the mean flow velocity $\bar{v}$:

$$U_0 \sim \int_{r=0}^{R} v(r) \cdot r \, dr \sim \bar{v}$$  \hspace{1cm} (1)

where $r$ is the radial coordinate and $R$ denotes the pipe radius. In order to obtain information on the spatial distribution of the velocity, the device is to generate a magnetic field of spatially varying magnitude as shown e.g. in Fig. 1b. This inhomogeneous field is applied in alternation to the homogeneous field inducing a voltage $U_1$ depending on the shape of the flow velocity profile $v(r)$:

$$U_1 \sim \int_{r=0}^{R} v(r) \left(\frac{r}{R}\right)^2 \cdot r \, dr \hspace{1cm} (2)$$

Consequently, a flowmeter with two alternately generated magnetic fields measures two quantities describing the flow velocity profile.

The realization in a commercial flowmeter requires only slight modifications of the sensor (see Fig. 1). Firstly, the direction of the current in one of the coils has to be switchable. Secondly, the electrodes, which are usually placed perpendicular to the coil axis, have to be placed at angles of $\pm 45^\circ$. Furthermore, the Eqs. (1) and (2) are given only for an ideal flowmeter which means a sensor with point electrodes and magnetic fields ideal formed. For a real sensor, however, the ideal weighting terms $g_0 = 1$ (cf. Eq. (1)) and $g_1 = (r/R)^2$ (cf. Eq. (2)) have to be substituted by a general weight function which must be calculated numerically [3].

RHEOLOGICAL MODELLING

The flow velocity profile is strongly influenced by the rheological properties of the material being processed. The flow behavior can be mathematically characterized by rheological models. A simple approximation is the power law model which is widely used to describe the non-Newtonian properties of fluids in theoretical analysis as well as in practical engineering applications [4]:
where \( \eta \) is the dynamic viscosity and \( \dot{\gamma} \) the shear rate. \( N \) denotes the power law index and \( K \) the consistency. Based on that model, a two-parametric function of the laminar flow velocity profile in a circular pipe is deduced:

\[
v(r) = \frac{1+3N}{1+N} \cdot R \cdot \left(1 - \left(\frac{r}{R}\right)^{1+1/N}\right).
\]

Both parameters, the power law index and the mean flow velocity, can be determined from the two voltages measured by the modified flowmeter. Additionally, a differential pressure sensor is mounted delivering the second rheological parameter, the consistency. The combination of both instruments represents the in-line process viscometer which allows the continuous measurement of the viscosity. Starting from the wall shear rate, the viscosity curve can be modelled over the relevant range of shear rate.

EXPERIMENTAL RESULTS

Tests with the presented measuring principle implemented to an electromagnetic flowmeter by Endress + Hauser (Promag 53 F, nominal width 50 mm) have been carried out in an experimental setup. A broad variety of fluids with different flow behaviour have been studied (sugar sirup, xanthan solution, luviskol solution, shampoo, tomato ketchup, mayonnaise, mustard). The viscosity curves of sugar sirup \((c = 10\%)\), 12% aqueous solution of luviscol (a thickening agent) and mustard are exemplarily plotted in Fig. 2. The solid lines represent the measurements of the in-line process viscometer with a flow rate of 1.0 l/s, which leads to a mean flow velocity of approximately 0.5 m/s. For the range of the shear rate existing in the pipe flow, these curves approximate very well the viscosity function measured with a laboratory rheometer (cone-plate geometry).

CONCLUSIONS

This paper has presented a measurement system that provides a non-invasive method to determine rheological parameters. Its main advantages are in-line and real-time operation, no moving parts, ease of cleaning and a simple hardware realization. The accuracy has been verified in experiments for a broad variety of materials. The system supplies results comparable to those obtained using a laboratory rheometer.

REFERENCES

4. Steffe J. F., Rheological methods in food process engineering, Freeman Press, 1992