

# CORIOLIS MASS FLOW METER WITH DIRECT VISCOSITY MEASUREMENT

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## Four process variables from one meter

Coriolis mass flowmeters are widely used in industrial flow measurement. Mass flow is measured directly with very high accuracy ( $\pm 0.1\%$  for liquids). These instruments are real multivariable meters, because all meters include direct temperature and density measurements as well. From these primary measured parameters, even further variables can be derived; e.g. concentration measurement based on density. The trend in industry shows an increased need for such multivariable instruments, which is due to increased global competition and, thus, requires better process efficiency and stricter quality control. Improving quality and process enables manufacturer to save costs by reducing production time and wasted material. Now, additionally to mass flow, density and temperature measurements, also **direct viscosity measurements** are successfully integrated into Promass 83 I, which is a single tube Coriolis mass flowmeter with a straight tube. Viscosity is a crucial process variable indicating important fluid properties like consistency, pourability and concentration, which can define the quality of a product. Viscosity can also be an important indicator for problems within a process and, thus, allows the manufacturers to adjust process parameters immediately to prevent a whole batch to be wasted. With these in-line measurements, no time is lost for separate laboratory viscosity measurement.

This paper explains the working principle of the new additional viscosity measurement and demonstrates its opportunities.

## Introduction

Coriolis meters offer the best accuracy in mass flow measurement. Due to the very good zero point stability of today's meters, this accuracy is obtained over a wide flow range. The physical principle of operation is very elegant, with no moving parts in the process subject to wear.

The tubes are oscillated in resonance. The resonance frequency gives information about density, which is also an important parameter for quality and process control. Coriolis mass flowmeters have proven to record density with excellent accuracy.

Endress+Hauser mass flowmeters can be applied to almost any application. For those applications, where accuracy, low pressure drop and good cleanability is needed, the single straight tube Promass I was introduced several years ago, which now serves as platform for the viscosity measurement.

The key of Promass I is the patented TMB™-balancing system of the meter (see Flomeko '98 proceedings for further details). A pendulum is attached to the middle of the oscillating measuring tube (see. Fig.1). This pendulum oscillates in counterphase to the tube, thus, is compensating the momentum of the measuring tube.

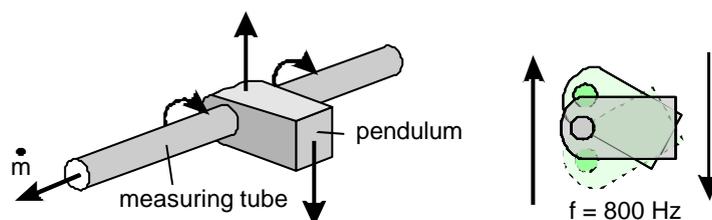


Figure 1 introducing torsional oscillation to balance the measuring tube (TMB™)

With the additional torsional oscillation, Promass I provides excellent vibration immunity over a wide density range.

The design of the Promass I sensor is shown in Figure 2. All wetted parts are made of titanium. The meter has a completely welded design with no gaskets in the process, and is therefore an ideal solution for hygienic processes.

The instrument is EHEDG certified, has 3A approval, and is available with a wide selection of hygienic process connections.

Promass I is also available as flanged version, and fulfils the requirement of hazardous area approvals (ATEX, FM, CSA) and PED certification, common in the chemical industry.

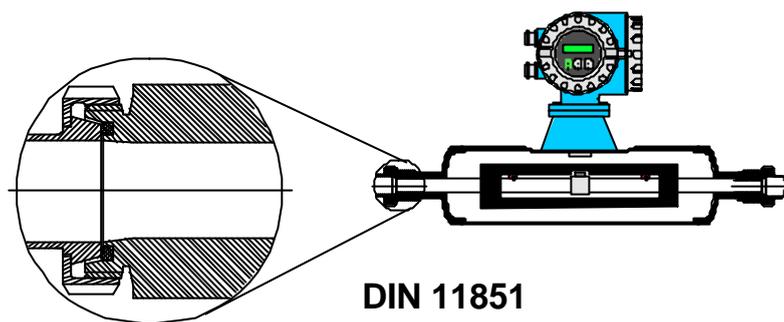


Figure 2 cross section of the meter; with DIN 11851 process connection as an example

#### Theory of operation of the viscosity measurement

Today's laboratory instruments are normally rotational viscometers, whereas in-line devices mostly operate based on oscillation principle. This is similar to the operating principle of the Promass I.

The torsional movement of the measuring tube can be utilised to measure the viscosity of the fluid. Figure 3 is a cross sectional view of the measuring tube. Due to the rotational motion  $v_{\theta}$  of the tube, the fluid is forced to a rotational motion. Depending on the viscosity, we find different velocity profiles  $v_{\theta}(r)$  of the fluid.

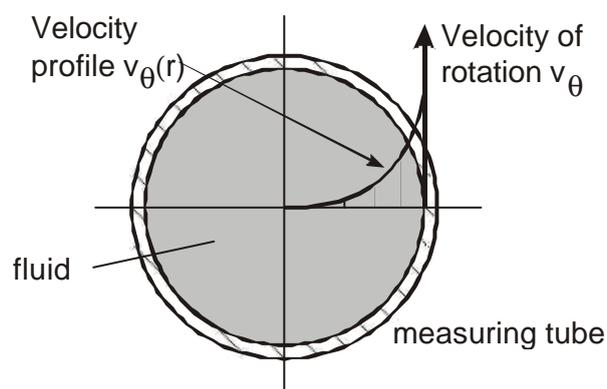


Figure 3 cross sectional view of the measuring tube and velocity profile  $v_{\theta}(r)$  of the fluid

The velocity profile can be calculated using Navier-Stokes equation. Under the assumption of constant density, constant viscosity and constant pressure we can evaluate the Navier-Stokes equation for the  $\theta$ -component. After several steps we arrive at:

$$\frac{\partial v_q}{\partial t} = \mathbf{u} \cdot \left[ \frac{\partial}{\partial r} \cdot \left( \frac{1}{r} \cdot \frac{\partial}{\partial r} \cdot (r \cdot v_q) \right) \right]$$

Evaluating this expression, we find that  $v_\theta$  is the solution of a partial differential equation of this type:

$$x^2 \cdot y'' + x \cdot y' + (x^2 - 1) \cdot y = 0$$

which is Bessels differential equation. Solving this differential equation and introducing the angle of torsional oscillation at the tube wall  $\theta_0$  we find the solution for the velocity profile  $v_\theta(r)$ , which for matter of simplification is not given here in detail:

$$v_q = fkt(f, r, q_0, \mathbf{u} \dots)$$

Using the above results, we can calculate the tube wall shear stress

$$\mathbf{t} = \mathbf{r} \cdot \mathbf{u} \cdot \left( \frac{\partial v_q}{\partial r} - \frac{v_q}{r} \right) = \mathbf{r} \cdot \mathbf{u} \cdot \frac{d\mathbf{g}}{dt}$$

Integrating the shear stress over the tube wall we obtain the momentum, which is necessary to oscillate the tube. Given the geometrical properties of the tube and the excitation system it is simple to derive a correlation between momentum and excitation current. Thus measuring the excitation current gives information about the viscosity of the fluid.

There is an difference between Newtonian and non-Newtonian fluids. For Newtonian fluids there is an analytical solution for the above mentioned function between viscosity and excitation current. The excitation current is dependent on the integral damping within the whole diameter of the tube. For non-newtonian fluids, the velocity profile also depends on the viscosity function. This means that the shear rate is a function of the viscosity of the fluid. The viscosity of non-Newtonian fluids measured with Promass I can still be determined with the above mentioned function, however one should take into consideration that the shear rate varies for different fluids.

#### Accuracy of the viscosity measurement

Applications for viscosity measurement can best be categorised through the fluid characteristic: Newtonian and non-Newtonian fluids. Promass I is calibrated with Newtonian fluids and measures the absolute viscosity of these. Due to the additional density measurement, the kinematic viscosity can be determined as well.

**Newtonian fluids.** Figure 4 shows results for the viscosity measurement. Four calibration fluids with different viscosities and also different densities were tested at the technical university Munich. The calibration fluids were the most accurate calibration fluids available (from Deutscher Kalibrier Dienst). An uncertainty of better than  $\pm 5\%$   $\pm 0,5$  cP was obtained with these Newtonian calibration fluids.

### viscosity error with different calibration fluids

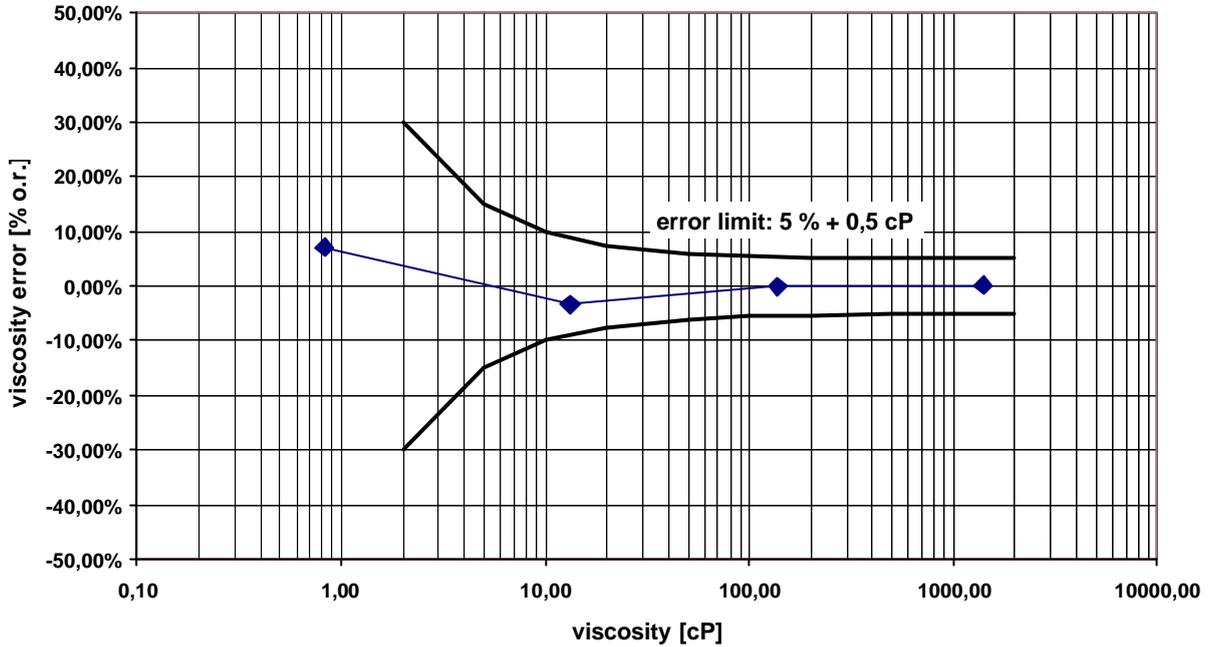


Figure 4 error of the viscosity measurement using different precision calibration fluids

Figure 5 demonstrates the possibility to control an in-line process. The viscosity of polyol is measured at different temperatures. Promass I is installed in the process, measuring the viscosity in-line. In parallel samples were taken for the reference viscometer. A very good correspondence was found between the two measurements. Both readings can be compared directly and are independent of shear rate, since polyol is a Newtonian fluid.

### viscosity of polyol over temperature

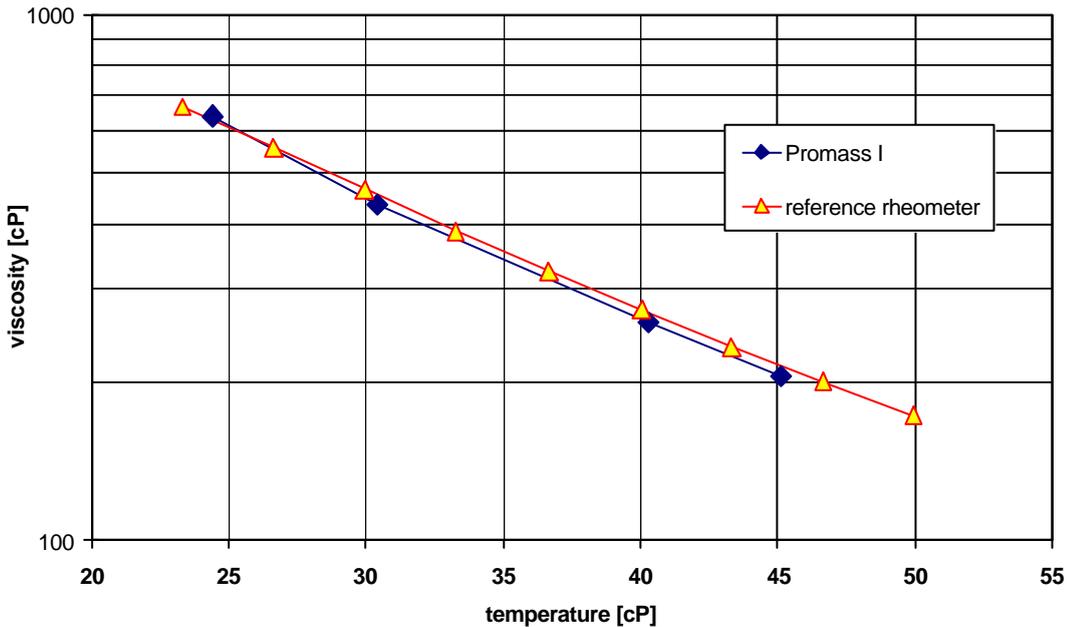


Figure 5 example for in-line process control of polyol

## Non-Newtonian Fluids

For non-Newtonian fluids the comparison between Promass I reading and laboratory viscometer is more difficult, because the viscosity of non-Newtonian fluids is dependent on the shear rate. However, viscosity of non-Newtonian fluids can also be measured in-line with good repeatability.

The comparison of results from different viscometers using different operating principles (e.g. comparison between laboratory and in-line measurements) is very complex, as the measured viscosity is depending on the specific shear condition of each viscometer. Whereas an empirical correlation between different viscosity readings is always possible, a mathematical correlation based on shear rates is a complex issue. Most often, mathematical models do not have the required accuracy to convert between results from different measuring principles.

For this reason, in-line viscosity measurements of non-Newtonian fluids are typically used in processes, where high repeatability is needed and where continuous correlations to laboratory measurement play a minor role; e.g., Promass I is used to look at a trend in the viscosity or to detect a change of the in-line viscosity, whereas the absolute value might differ from measurements taken with different viscometers. A change in viscosity may indicate a change in the process, which could lead to problems, or it may indicate that the product is outside the predefined limits of viscosity at this specific point.

## Conclusion

This new viscosity measurement feature, increases the multivariable functionality of the coriolis meter and, thus, offers customers the possibility to control their core process variables flow, density, temperature and viscosity with just one single meter. The robust design, vibration immunity, long term stability, as well as the easy to clean hygienic design are advantages known for coriolis meters, today, and are also important features when it comes to viscosity measurement. These advantages can lead to a significant reduction in installation and maintenance costs for various applications.

Figure 6 shows an example for the application of Promass I with direct viscosity measurement. In the feed pipe of a burning system the viscosity of the oil is measured to ensure an optimal combustion process. The same meter records oil consumption via flow rate, density of the oil and temperature. By regulating the temperature of the oil the optimal viscosity can be adjusted.

Figure 6:

application of Promass I for quality control of oil; simultaneous measurement of flow, density, viscosity and temperature



## Literature

Drahm, W.: New single straight tube coriolis mass flowmeter without installation restrictions. Proc. of the 9<sup>th</sup> International Conference of Flow Measurement, Flomeko '98, Lund, Sweden, June 15-17, 1998. S. 243-248.