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Flow meter for high-purity and aggressive liquids

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Abstract

We describe a new kind of flow sensor for liquids, which is based on a balance between hydrodynamic and magnetic forces. A floating body, containing a permanent magnet, is kept at constant position in a tube by an external solenoid. The current in the solenoid required to compensate the hydrodynamic force by a magnetic force is used as a measure for the flow rate in the tube. An integrated viscosity and density measurement allows an autocalibration, if liquids of unknown density or viscosity have to be measured. The only material in touch with the liquid is teflon, which allows measurements of highly aggressive media or such with high requirements to hygiene or purity.

The prototype covers a range of 20–250 ml/min and has a repeatability of ±0.5% full scale and an accuracy of ±1% full scale. The simple and modular design should lead to production costs which are significantly lower than those for other devices while offering the same performance.

Keywords: Flow sensor; Digital feedback control loop; Magnetic force

1. Introduction

Flow measurements in processes like etching, cleaning, chemical mechanical polishing and coating in semiconductor manufacturing and chemical industries require high performance flowmeters. Aggressive fluids such as hydrofluoric acid, sulfuric acid, nitric acid as well as different solvents require inert materials. In processes like chemical mechanical polishing (CMP) it is important that as little as possible external particles generated by the flowsensor reach the abrasive liquid (slurry). These particles could damage the silicon wafers, so it is advantageous to use flowmeters that do not have any moving parts or mechanical bearings like, e.g. a paddle-wheel sensor. A better solution is the use of ultrasonic sensors which measure the flow rate very precisely, but they are expensive. Other sensors that are used in semiconductor manufacturing need to be recalibrated, the whole process must be stopped.

Most flowmeters used today are paddle-wheel, vortex-, ultrasonic- and differential pressure sensors. The disadvantage of the differential pressure sensors compared with the ultrasonic devices is a higher pressure drop, moreover a precise flow measurement with an ultrasonic sensor depends on the flow profile and the price is much higher [1]. Vortex sensors cannot measure low flow rates, the Reynolds number has to be at least 4000—this corresponds to a typical limit of 300 ml/min [2].

In semiconductor manufacturing, there is an increasing interest in flowmeters that can measure very low flow rates, down to 20 ml/min, with an accuracy of at least ±2% of full scale. With our design there are no moving parts and the sensor does not have to be recalibrated periodically if there is no change in the fluid. These characteristics make our sensor attractive also for applications outside of semiconductor manufacturing.

2. Theory of operation

2.1. Principle

The principle of conventional rotameters is that a flow of fluid passes vertically upwards through a conical tube and a floating body takes up a definite position. The position depends on the weight of the floating body and its dimensions relative to those of the tube. The floating body is made to rotate by means of

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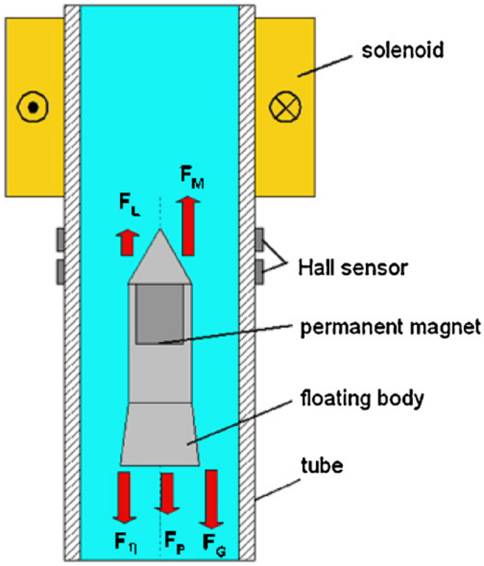

Fig. 1. Cross-section of the flow sensor. F_L is the buoyancy, F_M the magnetic force generated with the solenoid, F_η the drag force, F_P the pressure force and F_G is the gravitational force of the floating body.

nicks cut in its upper edge, so that it never touches the walls of the tube [3].

We developed a new flowmeter based on a different principle (Fig. 1): a floating body containing an axially polarized permanent magnet and a measurement tube surrounded by a solenoid. The fluid flow in the measurement tube exerts a force on the floating body depending on the flow rate. The solenoid generates a magnetic field which exerts a force on the floating body to compensate the hydrodynamic force. The position of the floating body is measured by Hall sensors and kept constant by a feedback control loop. By measuring the control current in the solenoid the fluid force and therefore the flow rate are precisely determined.

The floating body is freely suspended in the measurement tube. While the axial direction is controlled by active magnetic suspension, the floating body is centered in the radial direction by fluid forces. This principle avoids particle generation and prevents contamination of the liquid [4].

2.2. Fluid dynamic aspects

In the gap between floating body and tube wall there is a laminar flow profile. A flow of fluid causes a pressure drop that is calculated as [5]:

$$\Delta p = \frac{16 l \eta v}{d^2} \tag{1}$$

where l is the length of the floating body, η the dynamic viscosity of the fluid, v the mean flow velocity and d is the width of the gap.

The pressure force can be estimated as:

$$F_P = \Delta p\, R^2 \pi = \frac{16 l \eta v R^2 \pi}{d^2} \tag{2}$$

where R is the radius of the floating body.

The drag force F_η between floating body and tube wall in laminar flow can be calculated as:

$$F_\eta = \frac{4 l \eta v R \pi}{d} \tag{3}$$

Finally, the comparison between F_η and F_P:

$$F_P = F_\eta \frac{4R}{\mathrm{d}} \tag{4}$$

With the dimensions of our sensor the pressure force is dominant for the resulting fluid force, it is about 100 times higher than the drag force.

3. Flow meter design

3.1. Geometry

Considering the low flow that has to be measured, down to 20 ml/min, the gap between floating body and tube has to be very small. At the bottom of the float it is only 0.2 mm.

Compared with the conventional rotameter where a flow of fluid passes vertically upwards through the tube, in our prototype the flow is downwards. For every flow rate, even zero flow, the solenoid has to pull up the floating body. The permanent magnet is in the upper half of the floating body. According to this the magnetic force affects the floating body only in its upper half. So together with a flow of fluid the stall at the bottom of the floating body causes a torque on the floating body that centers it in the sensor tube—for flow rates down to 20 ml/min [6].

3.2. Choice of the floating body position

To determine the ideal control position of the floating body, the magnetic induction of a solenoid along the axis is calculated, based on Biot–Savart. Fig. 2 shows the result. The force on a permanent magnet in a magnetic field is:

$$F_M = m \frac{\partial B}{\mathrm{d}x} \tag{5}$$

with m the magnetic dipole moment of the permanent magnet.

This shows that the maximal force is obtained at the position with the highest field gradient.

The resulting force on the permanent magnet is shown in Fig. 3. The maximum of the magnetic force on the floating body results at the edge of the solenoid. With the digital feedback control loop the permanent magnet is controlled to that position.

3.3. Electronics of the sensor

The main part of the sensor electronics is a digital signal processor (DSP) which controls the position of the floating body and calculates the flow rate with the measured solenoid current. With temperature sensors, errors caused by fluctuations in temperature can be compensated.

The control loop is realized with a position controller (PID) and a current controller (PI). With the measured position the DSP calculates a current to hold the position, so the required