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Abstract—**This paper presents a noninvasive closed-loop flow control system in a compact design for high-purity or aggressive chemical applications. The novel topology with a solenoid activated valve and an ultrasonic-based flow measurement permits precise flow control with rapid response time at a very low price. In this paper, the mechanical setup, power electronics, implemented closed-loop control, and the measurement of flow and valve stroke are discussed. Finally, the performance of the system is verified by a laboratory prototype.**

Index Terms—**Actuators, electromagnetic forces, flow control, solenoids, ultrahigh purity.**

I. INTRODUCTION

AS A CONSEQUENCE of the rapidly increasing complexity and sensitivity of processes, industry branches like chemical, biotechnology, semiconductor, and pharmaceutical industries have tightened their purity requirements for process environments, particularly for fluid-handling systems. This development has also a significant impact on flow control systems which are used for delicate blending and dosing applications.

Such a flow control consists primarily of a valve and a flow measuring device. These parts must meet a set of tough requirements. Blending and dispensing tasks require high precision and rapid response. All wetted parts are required to withstand a wide range of aggressive chemicals, and particle generation due to abrasion of mechanical parts in valves must be prevented. For example, for chemical–mechanical polishing applications, liquids with fine-particle granulate (slurries) are used. Therefore, the deployed valves and flow meters must not exhibit any dead spot in order to avoid sedimentation or blockage. To make the flow controls usable for a wide range of applications, the valves should offer a wide adjusting range and a large pressure tolerance. If the flow control is deployed in a clean room environment, it should be very compact to keep the required space and the associated costs as low as possible. To facilitate continuous operation and to keep the operation costs low, the flow controls should also be low maintenance [1].

Today's commercially available flow controls can be divided into two major groups. The first group uses valves with moving mechanical parts to control the flow. The second group uses noninvasive methods to set the flow, for example, a valve with a membrane. Both groups have their advantages and disadvantages. With mechanical valves (e.g., needle valves, slide valves, rotary valves, etc.), the flow can be set very precisely and in a wide range. Depending on the actuator (e.g., hydraulic or pneumatic cylinder, stepper motor, etc.), the manipulation time can be low or high (1–5 s). A disadvantage of that group of valves is mechanical wear and possible dead spots. Wear contaminates the fluid, and dead spot leads to sedimentation and blockages. Moreover, this type of valve is hard to clean and sterilize. The second type controls the flow in a noninvasive manner by reducing the cross section of the valve with a membrane. This topology enables a hermetic encapsulated flow channel. Therefore, the danger of wear is eliminated. Most of these valves are propelled by a stepper motor, which makes them expensive, and the average response time rises to approximately 3 s [2]–[4].

The analysis of the commercially available flow controls reveals that the valves exhibit a high level of specialization. Therefore, for a specific application, there are only a small number of valves to choose. At the moment, there is no flow control available which offers accuracy, high dynamic, noninvasive flow channel, small construction volume, chemical resistance, and low price at the same time.

In this paper, a simple low-cost flow control setup (cf. Fig. 1) is presented, which meets all aforementioned requirements. The flow control is designed for delicate blending operation with a peristaltic pump. The typical system pressure and flow rate of such a system are about 1 bar and 1 L/min, respectively. The flow is set via a fast solenoid actuator which squeezes a chemical resistant tube. This setup guarantees a hermetic flow channel and a fast response time [5], [6] at a low price.

II. MECHANICAL SETUP

In Fig. 1, the principal mechanical setup is shown. The flow is controlled by squeezing a flexible tube with a solenoid actuator

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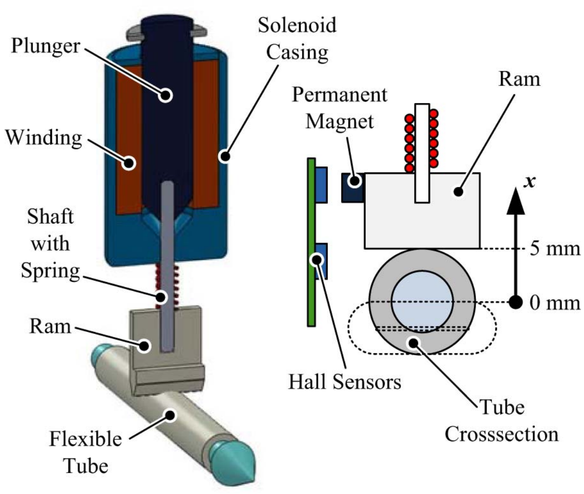

Fig. 1. Simplified mechanical setup of the solenoid operated valve. The flow is controlled by squeezing the flexible tube. At a stroke of $x = 0$ mm, the valve is totally closed, and at $x = 5$ mm, the valve is open.

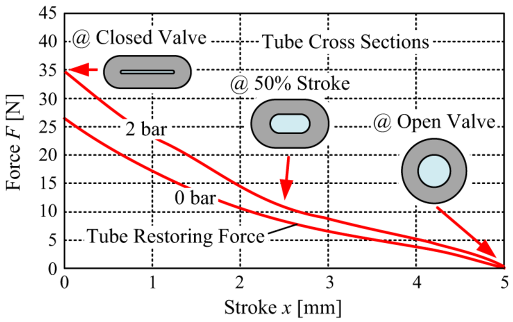

Fig. 2. Restoring force F of the tube in dependence of the solenoid stroke x. (The tube is totally open at $x = 5$ mm, and the tube is totally closed at $x = 0$ mm.)

[7]. The tube is made of a composite of platinum-cured silicone and polytetrafluorethylene. This material has a very smooth and slick surface, so that nearly no foreign particles are able to stick on it. Also, moisture and UV radiation do not cause a volume change or embrittlement. Moreover, the tube is resistant against a wide range of solvents and other aggressive chemicals and can be used in a temperature range from -200 °C to 260 °C [8].

To reduce the flow, a push-type solenoid actuator presses a plastic ram on the tube to reduce its cross section. The position of the ram is determined by the balance between the generated plunger force and the restoring force of the tube (cf. Figs. 2 and 4). In order to provide permanent contact between the ram and the tube, a spring is fixed on the shaft of the solenoid. A small permanent magnet is placed on the ram to enable the position measurement of the stroke with Hall sensors. The coordinate system of the stroke was defined in a manner that, at $x = 0$ mm, the valve is closed and, at a stroke of $x = 5$ mm, the tube remains undeformed (cf. Fig. 1).

With the electromagnet, only attractive forces can be produced. This means that, in the setup shown in Fig. 1, the ram can only be pressed onto the tube. However, there is no need for an additional reopening mechanism since the restoring force of the tube is high enough to open the valve sufficiently fast.

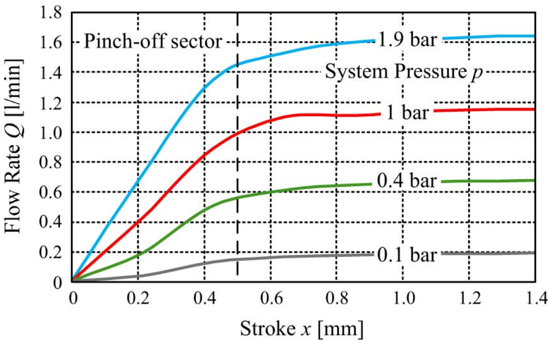

Fig. 3. Flow rate Q in dependence of the solenoid stroke x.

III. CHARACTERIZATION OF COMPONENTS

In order to select a suitable solenoid actuator, it is necessary to know how much force is necessary to totally close (squeeze) the tube. In Fig. 2, the restoring force of the tube in dependence of the solenoid stroke is shown. Between 0- and 2-bar fluid pressures, a force of 25–35 N is necessary. The total stroke is $x = 5$ mm.

In Fig. 3, the flow rate Q in dependence of the valve stroke x is depicted. It is shown that the flow rate Q can be adjusted with a stroke in the range of $0 \text{ mm} \leq x \leq 0.5$ mm. Strokes greater than $x = 0.5$ mm do not result in a higher flow, and the flow rate Q can be considered to be constant.

This phenomenon can be explained by examining the deformation of the cross section of the tube. At a stroke of $x = 5$ mm, there is no deformation of the tube. In the range of $0.5 \text{ mm} \leq x \leq 5$ mm, a deformation of the tube takes place. The shape is changing but the cross-sectional area is practically the same. As soon as the stroke is below $x = 0.5$ mm, the cross-sectional area is reduced and the flow rate Q starts falling, respectively. In this pinchoff sector (cf. Fig. 3) and within the targeted system pressure range ($0 \text{ bar} \leq p \leq 2$ bar), the flow rate Q is approximated as a linear function of the stroke x. In fact, for small pressure values, this is not perfectly the case, but as will be shown in Sections V and VI, the controller can handle this slight nonlinear behavior. Therefore, the flow rate in the pinchoff sector can be stated as

$$Q = k(p) \cdot x \qquad \forall\, 0 \leq x \leq 0.5 \text{ mm} \tag{1}$$

whereas k is a proportionality factor which depends only on the system pressure p.

To squeeze the tube, a standard solenoid with a nominal current of $I_N = 1.33$ A was chosen. In Fig. 4, the achievable plunger force F in dependence of the stroke x is shown. The measurement results show that the tube can be kept totally squeezed with about 50% to 75% of the nominal current, depending on the system pressure.

IV. DESIGN CONSIDERATIONS

The characterization of the tube reveals that the pinchoff sector is only about 0.5 mm of the total stroke (cf. Figs. 3 and 5). Therefore, it makes sense to presqueeze the tube by means of an adjustable mechanical stop to $x = 0.5$ mm. Thus, the ram can

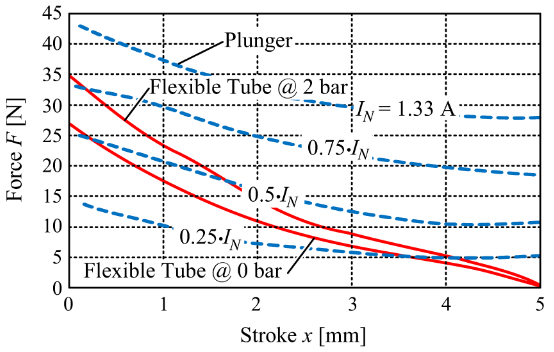

Fig. 4. Plunger force in dependence of the stroke x at various solenoid currents I and tube restoring force in dependence of the stroke x and system pressure p.

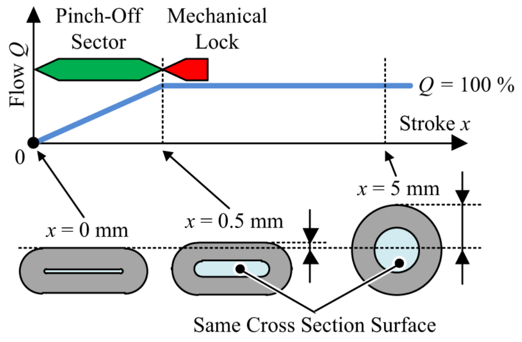

Fig. 5. Flow rate Q and tube cross section in dependence of the stroke x. For strokes greater than $x = 0.5$ mm, the flow Q can be considered as constant. Therefore, the maximal stroke can be limited mechanically to $x = 0.5$ mm.

only operate within the pinchoff sector (0 mm $\leq x \leq$ 0.5 mm; cf. Fig. 5). With that mechanical limitation of the stroke, the reaction time of the valve can be increased, and the power consumption of the solenoid can be reduced significantly. To fix the ram in position $x = 0.5$ mm with magnetic force instead of a mechanical stop, a power consumption of about 4–9 W would emerge. This is about 25% to 50% of the nominal power $P_N = 17$ W of the solenoid.

Fig. 3 shows that the selected tube with an inner diameter of $D_I = 5$ mm and an outer diameter of $D_O = 10$ mm is ideal for the targeted operating point (nominal flow rate $Q_N = 1$ L/min; nominal system pressure $p_N = 1$ bar). At a system pressure of $p = 1$ bar, the flow can be adjusted in the linear pinchoff area from 0 to 1 L/min.

In order to energize the solenoid, an adjustable power supply with a maximum output dc voltage of 48 V was selected. The nominal dc voltage of the solenoid is $U_N = 12$ V, and the temporarily allowable maximum dc voltage is $U_{\max} = 160$ V.

When designing the flow control, also the thermal stress of the solenoid must be considered. Since the tube can be kept squeezed permanently with not more than 75% of the nominal solenoid current (cf. Fig. 4), overheating in static operation is impossible. In steady-state operation, the input voltage of the solenoid is always below the nominal voltage U_N. However, during a transient sequence, a higher voltage can be permitted (up to 48 V) to increase the dynamics of the system. Therefore, during a rapid change of the ram position, the actual solenoid current may exceed the nominal value I_N. Considering the temperature of the solenoid, these short overcurrent peaks are acceptable as long as the rms value of the solenoid current

$$I_{\text{rms}} = \sqrt{\frac{1}{T}\int_{0}^{T} i^2(t)\,dt} < I_N \tag{2}$$

is smaller than the nominal solenoid current.

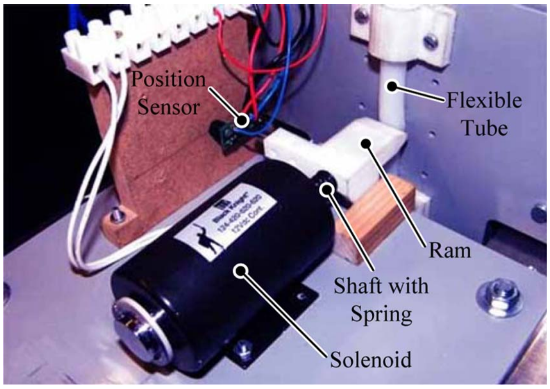

Fig. 6. Experimental setup.

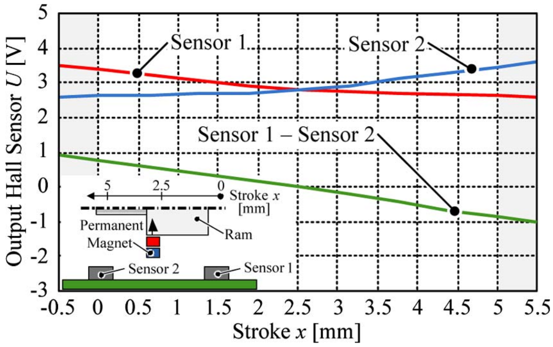

Fig. 7. Ram position detection with two Hall effect sensors.

V. Experimental Setup

In Fig. 6, the experimental setup of the flow control is shown. The solenoid is mounted perpendicularly to the tube and can reduce the flow rate by pressing the ram on the flexible tube. In order to measure the stroke, a small permanent magnet is fixed on the ram. The intensity of the magnetic field is detected by Hall sensors [9]. In order to increase the accuracy of position measurement, to reduce noise, and to get a linear dependence between stroke and the position signal, two sensors are deployed, whose output signals are subtracted from each other (cf. Fig. 7). Before the position signal is fed into an analog-to-digital converter (ADC) port of the programmable power supply, the signal is scaled to 0–3.3 V. This amplification leads to a resolution of 660 mV/mm.

Hall sensors are advantageous over eddy current sensors, particularly in terms of costs and realization effort, since eddy current sensors need an excitation and a complex analyses circuit [10].

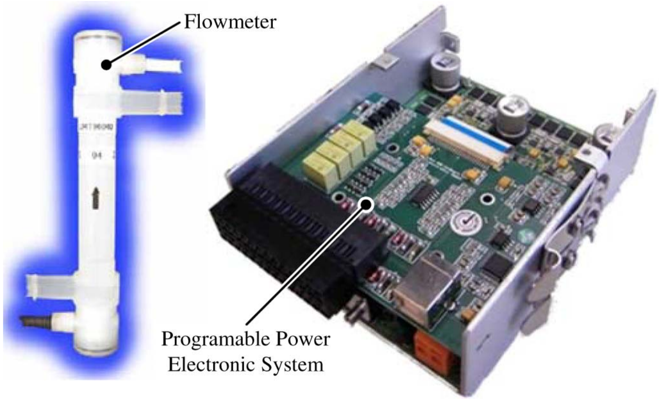

Fig. 8. Flow measurement device and programmable power electronics with a dc output voltage range of 0–48 V [11].

To establish a closed-loop flow control, a flow meter is necessary. In order to conserve the high-purity applicability, a noninvasive flow meter [11] is selected. The flow rate is deducted from the difference of the runtimes of an ultrasonic wave going downstream and one going upstream. The ultrasonic waves are generated and measured by combined piezoelectric transducer–receiver units. The used flow meter outputs a current signal depending on the flow rate. The flow range of the deployed meter is 0–4 L/min, and the output current is in the range of 0–20 mA. A shunt resistor (160 Ω) is used to gain a voltage signal (0–3.3 V), which can be directly connected to an ADC input of the programmable power electronics. With that configuration, a resolution of 1.2 L/(min · V) is achieved. In Fig. 8, the flow meter and the power electronics are shown.

The used programmable 200-W power electronic system consists of three main parts. The power board contains the driver circuit which energizes the solenoid. On the control board, a digital signal processor (DSP) and 5-V analog input/output drivers are placed. The third part is the communication board, which enables easy communication with a PC.

VI. CLOSED-LOOP CONTROL

Since the flow meter has a response time of about 500 ms, a subordinated position and a current controller are necessary to enable stable and fast operation. The position controller outputs the set point for the dc current, which is necessary to reach the desired ram position of the solenoid and, consequently, the desired flow rate. According to this set point, the current controller adjusts the dc output voltage of the supply. In Fig. 9, the schematic of the closed-loop control is shown.

When examining the equation of motion of the system (plunger acting against the tube)

$$m_{\text{plunger}} \cdot \ddot{x} = F_{\text{plunger}}(x) - F_{\text{tube}}(x) \tag{3}$$

it is obvious that the system can be considered as a second-order lag element which features the ability to oscillate. It can be stabilized with high dynamics by implementing a proportional–derivative position controller with the transfer function

$$G_{\text{PD}}(s) = K_p \cdot (1 + s \cdot T_d). \tag{4}$$

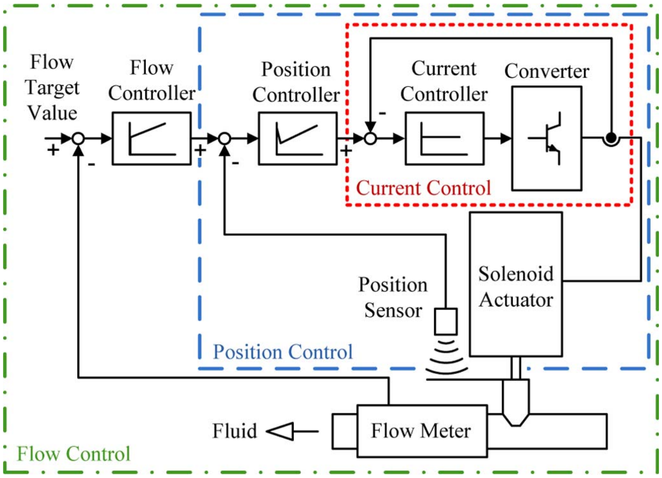

Fig. 9. Closed-loop control consisting of flow control circuit, position control circuit, and current control circuit. The control response times of the current control loop, position control loop, and flow control loop are about 2 ms, 10 ms, and 1 s, respectively.

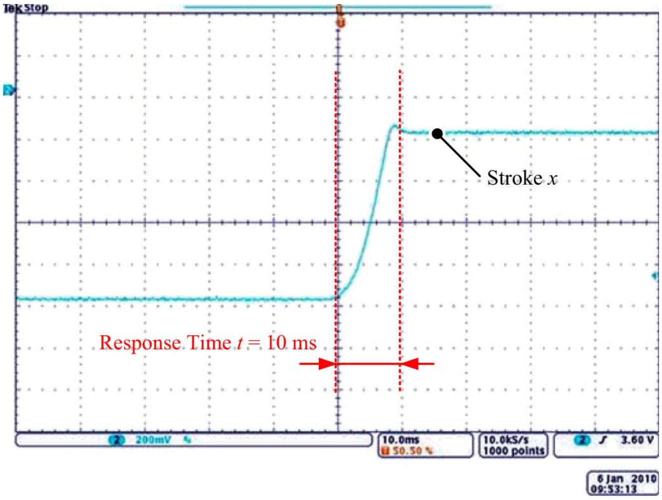

Fig. 10. Step response (from $x = 1$ mm to $x = 0.2$ mm) of the position controller (a stroke scale of -0.2 mm/div and a time scale of 10 ms/div).

The current controller and the flow controller are implemented as a proportional–integral controller with the transfer function

$$G_{\text{PI}}(s) = K_p \cdot \left(1 + \frac{1}{s \cdot T_i}\right). \tag{5}$$

A z-transformation in not necessary because the clock frequency of the DSP is high enough to consider the control as quasi-continuous.

VII. VERIFICATION

After setting up the flow control, the performance of the system was tested extensively. To verify the performance and the stability of the position control loop, the step response of the position controller was examined. In Fig. 10, an exemplary step response of the position controller is shown. It takes 10 ms to squeeze the tube from $x = 1$ mm to $x = 0.2$ mm.

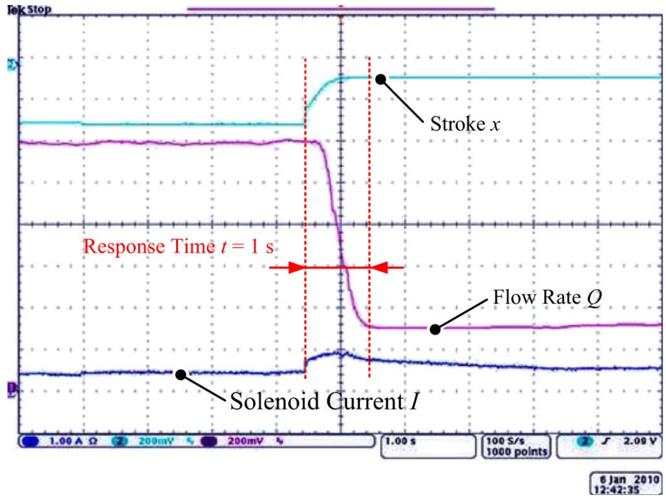

Fig. 11. System response time at a flow-rate step from 0.6 to 0.15 L/min (a current scale of 1 A/div, a flow-rate scale of 0.1 L/min/div, a stroke scale of -0.2 mm/div, and a time scale of 1 s/div).

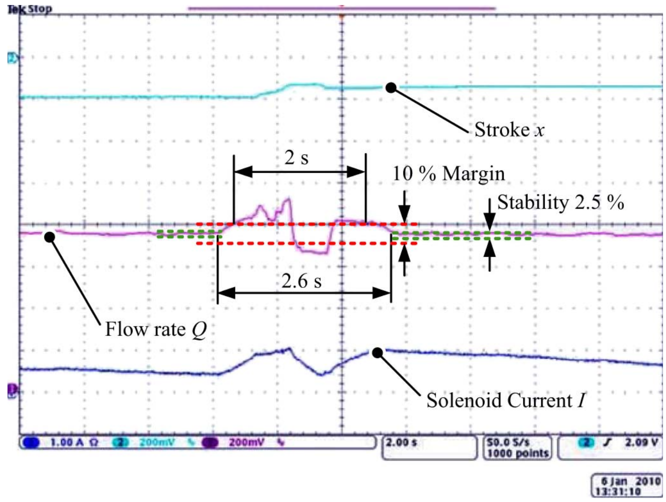

Fig. 12. Disturbance reaction at a pressure step form $p = 1$ bar to $p = 1.5$ bar at a flow rate $Q = 0.4$ L/min (a current scale of 1 A/div, a flow-rate scale of 0.1 L/min/div, a stroke scale of -0.2 mm/div, and a time scale of 2 s/div).

In order to test the performance of the whole flow control system, various flow-rate steps were executed, and the corresponding reaction times were measured. In Fig. 11, an exemplary flow-rate step is shown. At a system pressure $p = 1$ bar, it takes 1 s to reduce the flow rate from $Q = 0.6$ L/min to $Q = 0.15$ L/min. These results show that the introduced flow control is competitive to commercial available controls which exhibit a response time from 1 to 5 s [2]–[4].

Finally, the disturbance reaction of the control loop was investigated. Therefore, pressure changes were generated by varying the pump speed. In Fig. 12, an exemplary response to a pressure change is shown. The flow rate was set to $Q = 0.4$ L/min. The pressure was raised from $p = 1$ bar to $p = 1.5$ bar. After 2 s, the flow rate is again within a margin of 10% of the set point. After 2.6 s, the flow rate is equal to the target value again. The stability (relative deviation from the flow-rate set point) of the system is 2.5%.

VIII. CONCLUSION

In this paper, a very simple and low-cost flow control was presented, which meets a wide range of requirements of delicate fluid-handling applications. Next to the mechanical setup and the characterization of the used components, the closed-loop control was described in detail. The performance of the flow control was tested with an experimental setup. The results show that the flow control is competitive to high-standard commercially available flow control systems.

With the proposed high-purity flow control system, the benefits of other high-purity fluid-handling equipment, like bearingless pumps or bearingless mixers [11], can be maximized. So far, the missing link was a high-purity valve which is able to replace the common mechanical valves at a competitive price. By implementing this newly developed flow control system, the last big remaining pollution source in a fluid circuit can be eliminated successfully.

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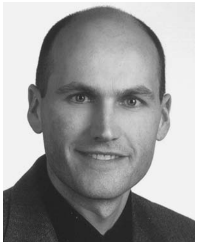

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From 2008 to 2009, he was with Levitronix Gmbh, Zurich, where he developed power supplies for magnetically levitated pump systems.

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Johann W. Kolar (M'89–SM'04–F'10) received the Ph.D. degree (*summa cum laude/promotio sub auspiciis praesidentis rei publicae*) from the University of Technology Vienna, Vienna, Austria.

Since 1984, he has been working as an Independent International Consultant in close collaboration with the University of Technology Vienna, in the fields of power electronics, industrial electronics, and high-performance drives. He has proposed numerous novel pulsewidth modulation converter topologies, and modulation and control concepts, e.g., the VIENNA rectifier and the three-phase ac–ac sparse matrix converter. He was appointed as a Professor and the Head of the Power Electronic Systems Laboratory, Swiss Federal Institute of Technology (ETH) Zurich, Zurich, Switzerland, on Feb. 1, 2001. He has published over 300 scientific papers in international journals and conference proceedings and has filed more than 75 patents. Since 2002, he has been an Associate Editor of the *Journal of Power Electronics* of the Korean Institute of Power Electronics and a member of the Editorial Advisory Board of the Institute of Electrical Engineers of Japan (IEEJ) *Transactions on Electrical and Electronic Engineering*. The focus of his current research is on ac–ac and ac–dc converter topologies with low effects on the mains, e.g., for power supply of telecommunication systems, More Electric Aircraft, and distributed power systems in connection with fuel cells. Further main areas are the realization of ultracompact intelligent converter modules employing the latest power semiconductor technology (SiC), novel concepts for cooling and EMI filtering, multidomain/multiscale modeling and simulation, pulsed power, bearingless motors, and power microelectromechanical systems.

Dr. Kolar is a member of the IEEJ and the Technical Program Committees of numerous international conferences in the field (e.g., the Director of the Power Quality Branch of the International Conference on Power Conversion and Intelligent Motion). From 1997 through 2000, he served as an Associate Editor of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, and since 2001, he has been an Associate Editor of the IEEE TRANSACTIONS ON POWER ELECTRONICS. He was the recipient of an Erskine Fellowship from the University of Canterbury, Christchurch, New Zealand, in 2003, and the Best Transactions Paper Award from the IEEE Industrial Electronics Society in 2005. In 2006, the European Power Supplies Manufacturers Association awarded the Power Electronics Systems Laboratory, ETH Zurich, as the leading academic research institution in Europe.