HIGH-DYNAMICS LOW-COST FLOW CONTROL WITH SOLENOID ACTUATOR FOR ULTRA-HIGH PURITY APPLICATIONS

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Abstract

This paper presents a non-invasive 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 ultrasonic-based flow measurement permits precise flow control with rapid response time at a very low price. In the paper the mechanical setup, the power electronics, the implemented closed loop control as well as the measurement of flow and valve-stroke is discussed. Finally, the performance of the system is verified by a laboratory prototype.

1 Introduction

In consequence of the rapidly increasing complexity and sensitivity of processes, industry branches like chemical, biotechnology, semiconductor and pharmaceutical industry have tightened their purity requirements for process environments, especially 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. E.g., for chemical mechanical polishing (CMP) applications liquids with fine-particle granulate (slurries) are used. Therefore, the deployed vents 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 vents 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 vents with moving mechanical parts to control the flow. The second group uses non-invasive 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 to 5 seconds). 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 vent is hard to clean and to sterilize. The second type controls the flow in a non-invasive 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 three seconds [2-4].

The analysis of the commercially available flow controls reveals that the vents exhibit a high level of specialization. Therefore, for a specific application there are only a small number of vents to choose. At the moment there is no flow control available which offers accuracy, high dynamic, non-invasive 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 as system is 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 fast response time [5,6] to a low price.

2 Mechanical Setup

In Fig. 1 the principal mechanical setup is depicted. The flow is controlled by squeezing a flexible tube with a solenoid actuator [7]. The tube is made of a composite of platinum cured silicone and polytetrafluorethylene (PTFE). This material has a very smooth and slick surface whereby 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 dissolvers and other aggressive chemicals and can be used in a temperature range from -200 °C to 260 °C [8].

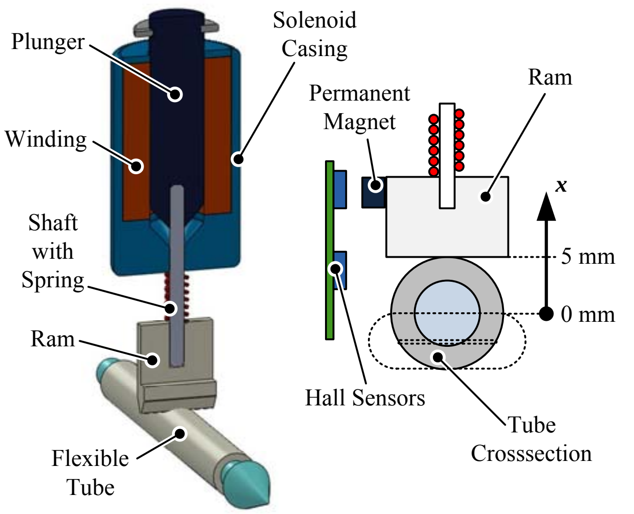

Fig. 1: Simplified mechanical setup of the solenoid operated valve. The flow is controlled by squeezing the flexible tube. At a stroke of $x = 0$ mm the valve is totally closed and at $x = 5$ mm the valve is open.

In order to reduce the flow a push-type solenoid actuator reduces the cross section of the tube by pressing with a ram made of plastic onto it. 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 places on the ram to enable the position measurement of the stroke with hall sensors.

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.

3 Characterisation 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 dependency of the solenoid stroke is depicted.

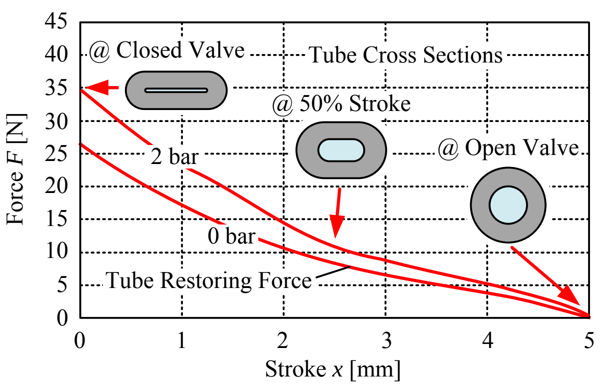

Fig. 2: Restoring force of the tube in dependency of the solenoid stroke. (Valve totally open @ $x = 5$ mm and valve totally closed @ $x = 0$ mm)

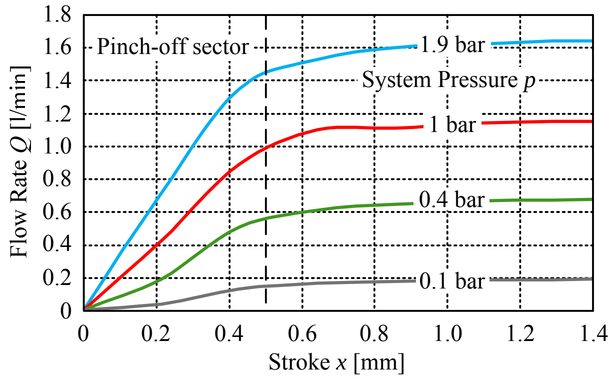

Fig. 3: Flow rate Q in dependency of the solenoid stroke x.

Between 0 and 2 bar fluid pressure a force of 25 N to 35 N is necessary. The total stroke is $x = 5$ mm.

In Fig. 3 the flow rate Q in dependency of the valve stroke x is depicted. One can see that the flow rate Q can be adjusted with a stroke in the range of $0 \text{ mm} \le x \le 0.5$ 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 $0.5 \text{ mm} \le x \le 5$ mm a deformation of the tube takes place. The shape is changing but the cross section area is practical the same. As soon as the stroke is below $x = 0.5$ mm the cross section area is reduced and the flow rate Q starts falling respectively. In this pinch-off sector the flow rate is given by

$$Q = k(p) \cdot x \quad \forall\; 0 \le x \le 0.5\,mm \tag{1}$$

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 dependency of the stroke x is depicted. 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.

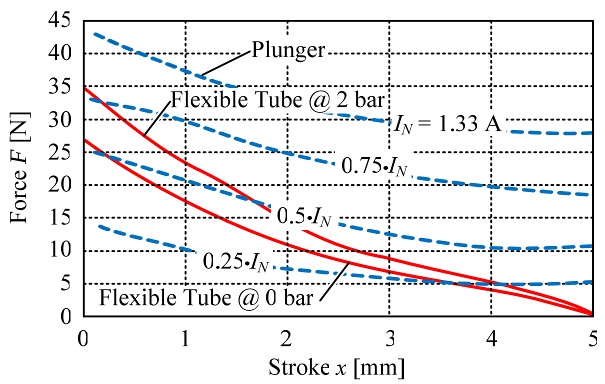

Fig. 4: Plunger force in dependency of the stroke x at various solenoid currents I and tube restoring force in dependency of the stroke x and system pressure p.

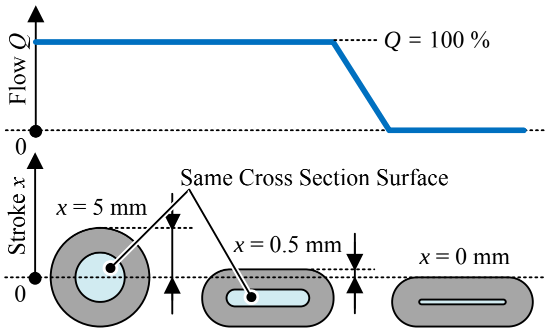

Fig. 5: Flow rate Q and tube cross section in dependency of the stroke x. The tube can be squeezed to $x = 0.5$ mm without reducing the flow rate Q.

4 Design Considerations

The characterization of the tube reveals that the pinch-off sector is only about 0.5 mm of the total stroke (cf. Fig. 3 and Fig. 5). Therefore it make sense to pre-squeeze the tube mechanically to $x = 0.5$ mm. 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 lock a power consumption of about 4 W to 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 pinch-off area from 0 to 1 l/min.

In order to energize the solenoid an adjustable power supply with a maximum output voltage of 48 V was selected. The nominal voltage of the solenoid is $U_N = 12$ V (max. permissible peak voltage $U_{max} = 160$ V). With that quadruple over-excitation a high dynamic and stable operation is enabled.

When designing the flow control also the thermal stress of the solenoid must be considered. Because 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 dynamic operation, rapid changing of the ram position may cause current peaks greater than the nominal solenoid current. Considering the temperature of the solenoid, these short peaks are acceptable as long as the RMS-value of the solenoid current

$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T i^2(t)\, dt} < I_N \tag{2}$$

is smaller than the nominal solenoid current. However, due to the slow flow control dynamics (cf. section 6) in practical operation conditions overheating does not occur.

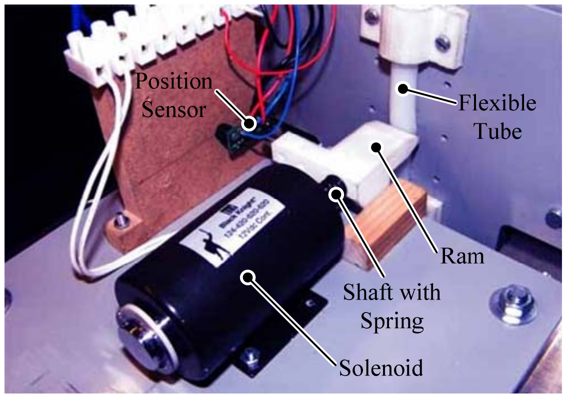

Fig. 6: Experimental Setup

5 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 dependency 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 ADC port of the programmable power supply the signal is scaled to 0 V – 3.3 V. This amplification leads to a resolution of 660 mV per mm.

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

To establish a closed loop flow control a flow meter is necessary. In order to conserve the high-purity applicability a non-invasive flow meter [11] is selected. The flow rate is deducted from the difference of the runtime 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 to 20 mA. A shunt resistor (160 Ω)

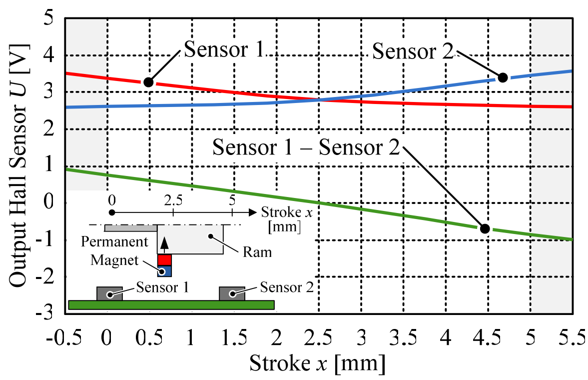

Fig. 7: Ram position detection with two hall effect sensors.

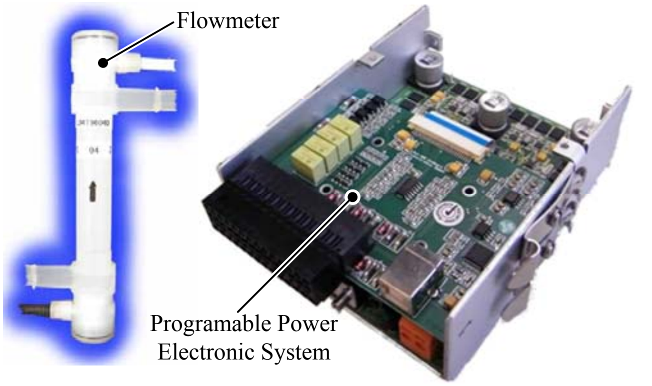

Fig. 8: Flow measurement device and programmable 48 V power electronics.

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 depicted.

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.

6 Closed Loop Control

Since the flow meter has a response time of about 500 ms, a subordinated position and current controller are necessary to enable stable and fast operation. In Fig. 9 the schematic of the closed-loop control is depicted.

Considering the position control loop, a proportional-derivative controller with the transfer function

$$G_{PD}(s) = K_p \cdot (1 + s \cdot T_d) \qquad (3)$$

was implemented in order to stabilize the instable magnetic plant. The current controller and the flow controller are implemented as a proportional-integral controller with the transfer function

$$G_{PI}(s) = K_p \cdot (1 + \frac{1}{s \cdot T_i}) \,. \qquad (4)$$

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

7 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

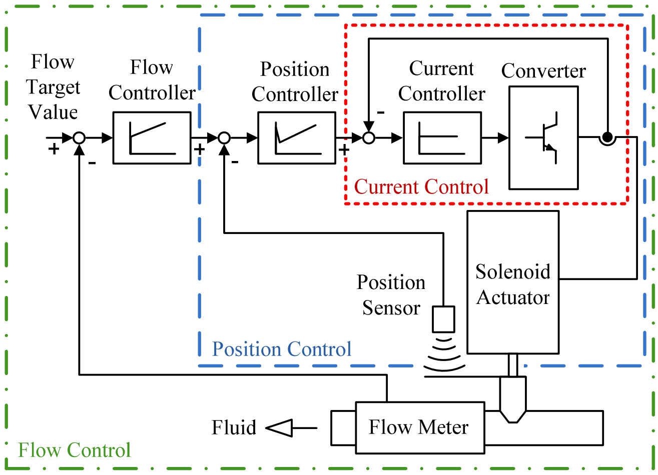

Fig. 9: Closed-loop control consisting of flow control circuit, position control circuit and current control circuit. The control response time of the current control loop is about 2 ms, of the position control loop about 10 ms and of the flow control loop about 1 s.

step response of the position controller is depicted. It takes 10 ms to squeeze the tube from $x = 1$ mm to $x = 0.2$mm.

In order to test the performance of the whole flow control system various flow rate steps were executed and the corresponding reaction time was measured. In Fig. 11 an exemplary flow rate step is depicted. 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 s 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 depicted. The flow rate was set to $Q = 0.4$ l/min. The pressure was risen 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 flow rate set point) of the system is 2.5 %.

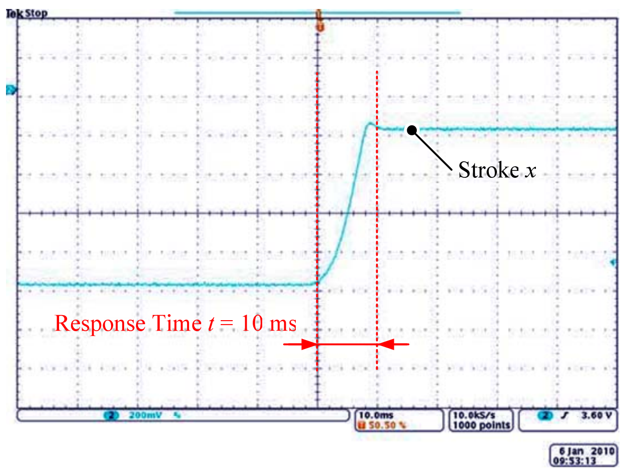

Fig. 10: Step response (from $x = 1$ mm to $x = 0.2$ mm) of the position controller (stroke scale -0.2 mm/div and time scale 10 ms/div).

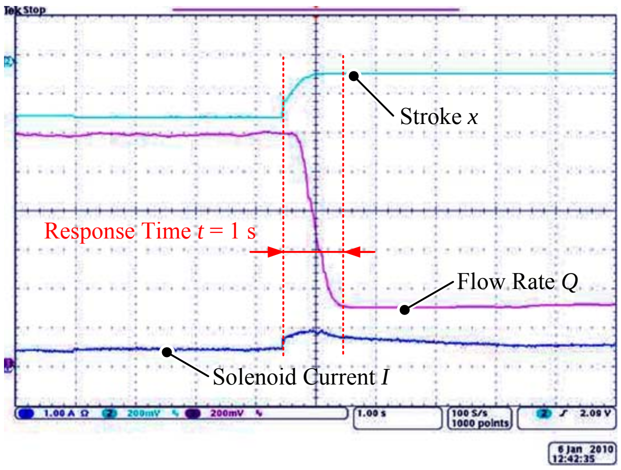

Fig. 11: System response time at a flow rate step from 0.6 l/min to 0.15 l/min (current scale 1 A/div, flow rate scale 0.1 l/min/div, stroke scale -0.2 mm/div and time scale 1 s/div).

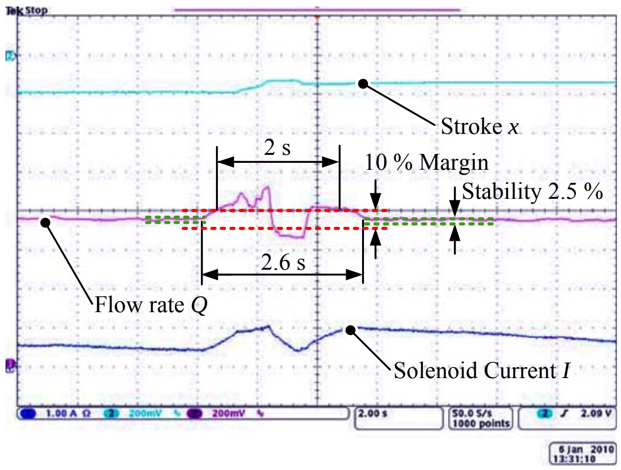

Fig. 12: Disturbance reaction at a pressure step form $p = 1$ bar to $p = 1.5$ bar at a flow rate $Q = 0.4$ l/min (current scale 1 A/div, flow rate scale 0.1 l/min/div, stroke scale -0.2 mm/div and time scale 2 s/div).

8 Conclusion

In this paper a very simple and low cost flow control is 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 is 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 high-purity flow control systems.

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