PRECISE DOSAGE SYSTEM FOR CONTROLLED LIQUID DELIVERY BASED ON FAST MEMS BASED FLOW SENSOR

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ABSTRACT

We present a system approach for precise liquid dosing at low costs. The highly integrated system operates at flow rates of 0-10mL/min and with a back pressure of 0-75kPa. It enables a flow with significantly reduced pulsation and a maximum deviation of 1.5%. The realization of the system is based on a smart combination of commercially available low cost fluidic components with a MEMS based thermal mass flow sensor of 1ms response time.

KEYWORDS

pump, valve, flow sensor, dosing system, metering

INTRODUCTION

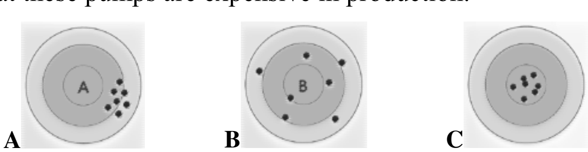
In many applications there is a need for controlled dosage of liquid media. An example of this can be seen in fuel cell reformers, where educts have to be delivered at controllable rates with low pulsation [1].

State of the art

The metering of liquids can be classified to 3 different types of systems.

Low-end pumps are used to transport liquids without the knowledge of the flow rate. Usually they are combined with a liquid level sensor and have a simple on/off control feature. At present, the usage of low cost pumps is not possible for metering tasks, because they are very imprecise and produce a significant flow pulsation. Examples are peristaltic [2] or diaphragm [3] pumps.

High precision pumps (metering pumps), for example piston [4] or gear [5,6] pumps, feature increased metering precision (figure 1) due to the exploitation of precision mechanics. Many of them are described with a precision in the range of 1%. The small spaces between the moving displacement parts have helped to achieve a high back pressure. The technical effort implicates the disadvantage that these pumps are expensive in production.



A B C

Figure 1: Illustration of the difference between high precision (A) respectively high accuracy (B) [7]. In (C) both a high precision and high accuracy are achieved.

The third group includes closed loop controlled dosing systems. Contrary to metering pumps, the flow rate is additionally measured and the pump is driven to reach the set point. Hence the accuracy (figure 1) of these systems is improved. The dependency on back pressure and viscosity is minimized. Examples are mass flow controllers (MFC) [8] and a few other devices [9]. The MFCs on the market at present usually have large dimensions, high energy demand and are expensive [10].

Liquid dosing system requirements

A dosing system should have the following characteristics: To start with, both the accuracy and the precision should be as high as required. Then, it should cover a wide dynamic range of flow rates. The dependencies from back pressure and viscosity should be low. Additionally, a low pulsation and consistent flow rate is desirable. Finally, the ratio between costs and performance should be adequate.

From macro to micro pumps

In oil hydraulics, for example, pumps for several L/min are used. These pumps are considered as constant volume displacement pumps. This assumption can be made as the leakage through the sealings and in the check valves can be neglected compared to the metered liquid.

The first method that can be used to reduce this flow rate is to minimize the displacement volume. However this procedure has limits. An example of this limit being exceeded is in small piezo diaphragm pumps [11,12] where the flow rate becomes highly dependent from the fluidic load. Another possibility is to reduce the displacement frequency, but this contradicts to the claim on low pulsation and consistent flow rate. Furthermore at low frequency extensive pulsation dampening is required.

Therefore several additional flow reduction methods are used [13]. The easiest approach is to increase the back pressure of the pump with control valves. But for positive displacement pumps this is not suggested.

Another approach is to use a bypass and thus dividing the flow into a portion flowing to the outlet and the rest flowing back to the tank. A pressure control valve is arranged in the bypass (parallel to the pump) and adjusts the back pressure to a fixed value. When there is an additional control valve in series to the pump the output flow rate can be controlled [14].

However, the bypass approach has several disadvantages. First, it leads back to the tank, so the complete dynamic and potential energy of the moving fluid in the bypass is converted to heat. Secondly, two tubes are needed. With only one tube connected to the tank the self priming characteristic is disturbed because air circles in the bypass. Finally, the bypass pressure drop has to be accounted as it effects the maximum load pressure. This leads to a high energy demand and short life time of the pump.

SYSTEM CONCEPT

The presented system can be regarded as an improved bypass solution. Most of the drawbacks of the classic bypass are eliminated.

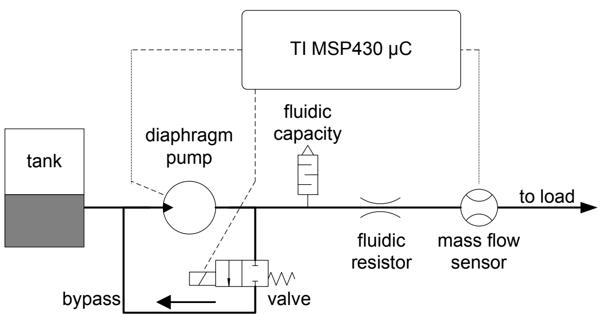


Figure 2: Flow chart of the presented dosing system.

As can be seen in figure 2, a 2/2-way control valve (VA204 [15]) is connected in parallel to the pump. Hence, the flow is divided [16]. One part flows to the load and the other flows back through the valve directly to the suction side of the pump. Consequently, only the pressure energy is wasted, but the fluid stays moving. The ratio between the two flows can be adjusted with the valve by pulse width modulation (PWM) and with the constant fluidic resistor. The pressure drop at the valve is automatically adjusted depending on the load. If the control valve is completely closed, the bypass is not existent and the pump stays self priming.

The output mass flow is measured with the sensor. A microcontroller reads out the actual flow rate and controls the valve in order to adjust the flow rate to set value. To extend the dynamic range of the dosing system, the controller also varies the frequency of the pump.

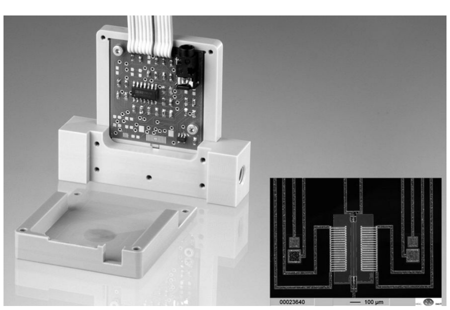


Figure 3: Thermal mass flow sensor [18] with electronics.

REALISATION

A low cost pump (NF5 DCB-4 [17]) is used to supply liquid from a reservoir to the load. This pump is oversized in terms of flow rate. In comparison to smaller low cost pumps, however it has a max. back pressure of 100kPa. To damp pressure pulses, a fluidic capacitance is used. It consists of a circular membrane with deformable foam on the back side. Since the pump is actuated with a frequency between 30Hz and 40Hz, a response time of about 1ms is needed by the sensor. To accomplish this we used a very fast MEMS based thermal flow sensor [18] to measure and control the flow rate of the complete system.

For closed loop control a MSP430 [19] is used to measure the sensor output and to control the valve and pump. To avoid interaction between the pump and valve (beating output flow due to interference) both are synchronized in frequency. This is described in [20].

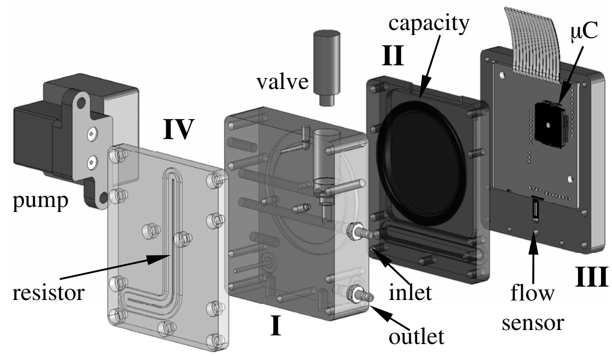


Figure 4: CAD drawing of the realized system.

The functional components are implemented in different layers to reach a high integration grade (figure 4, figure 5). Component I includes the valve, inlet and outlet ports and the bypass. It is connected directly to the pump. Component II contains the circular foam and membrane of the fluidic capacitor and, on the other side, the flow channel above the sensor chip. Component III comprises of the flow sensor chip and the complete electronics assembly. Component IV includes only an o-ring sealed rectangular flow channel used as fluidic resistor. This allows the resistor to be easily exchanged. In future devices this resistor could be realized as capped channel or as steel capillary tube inside component I to reduce the number of components.

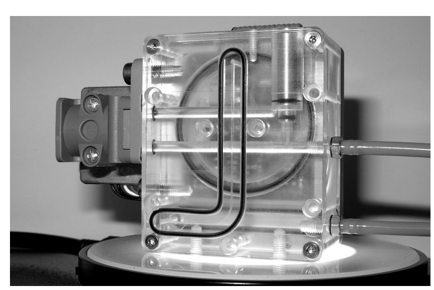


Figure 5: Real system made of PMMA. The physical dimensions are 50mm x 42mm x 27mm (without pump).

FLOW CALCULATION

Due to the thermal principle the flow sensor has to be calibrated. The target flow rate was generated with a syringe pump (Nemesys [21]) and the sensor output was recorded. One exemplary calibration curve is shown in figure 6. With this fit-curve a "look up table" was created, which relates a flow rate in mL/min to every possible 4095 A/D converter integer steps.

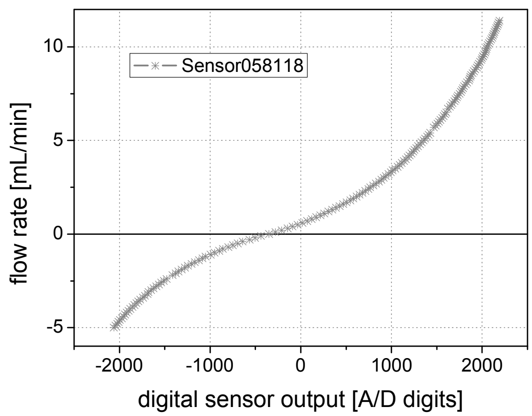


Figure 6: Calibration curve of Sensor 058-118.

Because of the non-linearity of the calibration curve it is not sufficient to average the raw sensor data. This would cause an error in flow rate calculation. Instead 32 A/D sensor values are recorded during every stroke of the pump, converted to flow and integrated (figure 7). The resulting sample rate is about 1kHz. With this procedure, the integrated flow value of one single pumping stroke can be exactly calculated, even if the flow is partly negative (not shown). Based on this result the opening time of the valve for the next pump stroke is calculated with a closed loop PID controller.

Although the pump itself is imprecise and the displacement volume varies slightly with every stroke, the set point is reached at average value due to the controller.

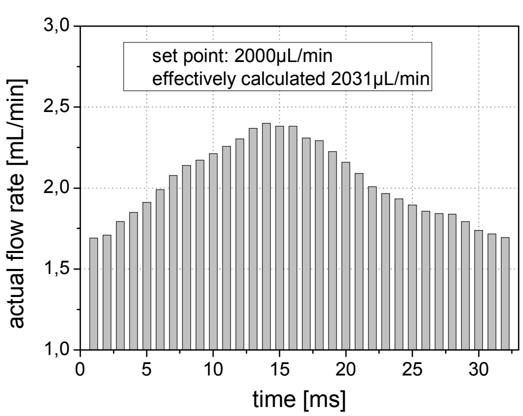


Figure 7: During one stroke of the pump, 32 single flow rates are measured. By integration of the area below this curve the stroke volume is calculated.

EXPERIMENTAL RESULTS

A precision balance (ED623S [22]) was used as reference. Figure 8 shows the comparison between the syringe pump and the balance, respectively the output signal of the flow sensor (without pump, valve and bypass). It can be seen that the syringe pump can also be used as reference, since the deviation between the flow rates generated with the syringe pump and the flow rates measured with the balance is about 0.1% and thus about one order of magnitude lower than the required accuracy of the flow sensor. The flow sensor itself (calibrated with syringe pump) shows an accuracy of about 1%.

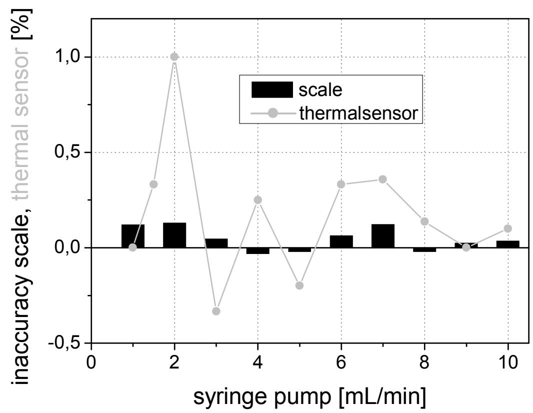


Figure 8: Accuracy of the syringe pump, respectively the sensor.

Then, the dosing system was used to meter water from the scale into a reservoir. In this tank, the pressure is adjustable. Thereby very fast back pressure changes can be given to the system. The set point is adjusted via RS232.

In figure 9, it can be seen how the flow rate is in accordance with the set point. After 5s, the new value of 5mL/min is achieved. Strong changes in back pressure also affect the flow rate. This disturbance is compensated in max. 5s.

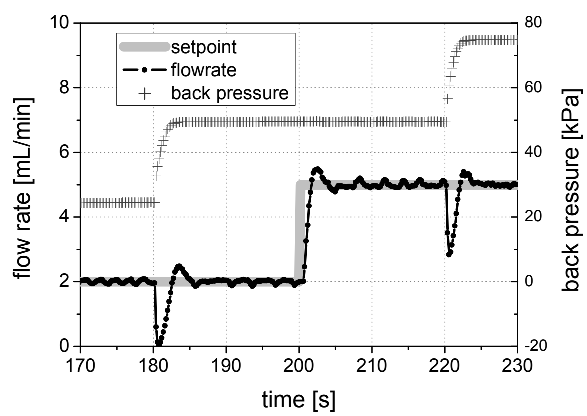


Figure 9: Flow rate measured by the sensor against set point and back pressure.

In figure 10, the variation coefficient of the flow rate (set point: 2mL/min, back pressure: 25kPa) is shown. The dosing precision varies with back pressure and the deviation is within 1.5% of set point. The accuracy accords to the sensor accuracy described in figure 8.

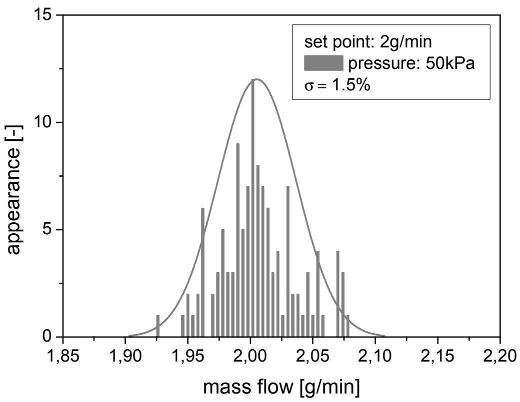


Figure 10: The standard deviation of 120 measurements, a set point of 2mL/min and a back pressure of 50kPa is shown.

CONCLUSIONS

We demonstrated a novel liquid dosing system approach. The accuracy and precision is not reached with an expensive metering pump, but by using a very fast MEMS based thermal mass flow sensor combined with a modified and improved bypass solution. So an oversized and imprecise pump can be used. The advantages of this pump are the achievable high pressure, the lower back pressure dependency compared with smaller pumps and finally the low price.

The metering accuracy and precision are almost independent from the pump itself. They are coupled to the flow sensor element. This can be seen as a drawback, because the metering accuracy is limited by the sensor accuracy.

The goal of this system approach is to substitute metering pumps in applications, where a process control is desired. At the moment, this is not provided by a single pump since a flow sensor is missing.

Due to the usage of low cost components, a target price below the range of precision metering pumps seems realistic.

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