A LOW-COST, NORMALLY CLOSED, SOLENOID VALVE FOR NON-CONTACT DISPENSING IN THE SUB-µL RANGE

S. Bammesberger[1], *S. Kartmann*[1], *L. Tanguy*[1], *D. Liang*[3], *K. Mutschler*[1], *A. Ernst*[1,2], *P. Koltay*[1,2] *and R. Zengerle*[1,3]
[1] University of Freiburg, IMTEK - Department of Microsystems Engineering, Freiburg, Germany
[2] Biofluidix GmbH, Freiburg, Germany
[3] HSG-IMIT - Institut für Mikro- und Informationstechnik, Freiburg, Germany

ABSTRACT

We present a disposable, normally closed, non-contact dispensing valve for the sub-µl range. The miniaturized solenoid valve (diameter: 8 mm, height: 27.25 mm) is compatible to standard Luer-Lock interfaces. The experimentally determined minimal dispensing volume was 163 nl (CV 1.6%) for water and 123 nl (CV 4.5%) for 66% (w/w) glycerol/water. Its modular design allows the reuse of components and actuators that are not contaminated by the reagent. Low-cost polymer components in contact with the reagent during the dispensing process can be considered as disposables, rendering expensive washing steps unnecessary and reducing risk of cross-contamination.

KEYWORDS

Non-contact dispensing, low-cost, disposable, solenoid valve, normally closed

INTRODUCTION

Dispensing valves for biomedical applications are facing demanding requirements in terms of minimal volume, precision and accuracy [1]. For most applications, dispensing valves need to be normally closed requiring rather complex closing or return mechanisms. Additionally, the avoidance of cross-contamination is crucial giving preference to non-contact dispensing systems. Piezo actuated or solenoid dispensing valves are the preferred technologies to address these requirements due to their highly dynamic and precise behavior [2,3]. Most of the commercially available systems feature complex and expensive designs, materials and mechanisms and therefore need to be washed and reused. These washing procedures decrease throughput and increase the risk of cross-contamination. Due to the simple design and the low-cost materials, the valve presented here could be used as a disposable enabling carry-over free reagent dispensing without expensive and time consuming washing steps.

WORKING PRINCIPLE

Fig. 1 depicts the working principle of the dispensing valve. The inlet of the valve is pressurized at a constant pressure level. This actuating pressure is released when the valve is being opened. Opening is achieved by a movable ferromagnetic plunger that is pushed upwards by electromagnetic actuation to open the upper end of a metal capillary which forms the valve seat. The solenoid valve is normally closed, i.e. a ferromagnetic ring magnet attracts the plunger and pulls it downwards if the actuating electrical coil is not energized. If the actuating coil is energized, a magnetic field is induced which overcomes the attractive force of the two permanent magnets to open the valve and to release the pressure.

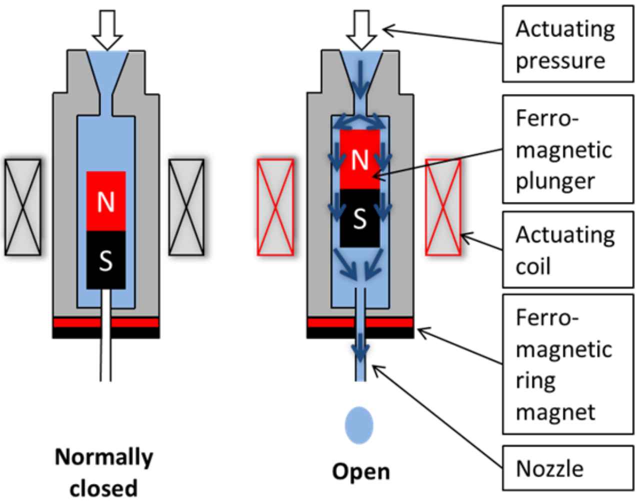

Figure 1: Working principle of the dispensing valve. Left: In its normally closed state, the ring magnet attracts the plunger and the valve seat is closed. Right: The actuating coil overcomes the attractive force between the ring magnet and the plunger to open the valve.

The coil is energized by an electrical current in form of a “peak-and-hold” square-wave, i.e. the signal starts with a peak current of 10 A which is reduced to a hold current level of 2.7 A after 5 ms. Applying a higher current especially at the beginning of the actuation pulse, where the inductivity of the solenoid and the attractive force of the permanent magnet needs to be overcome, allows for a dynamic movement of the plunger. The lower hold current reduces heat coupling effects that can lead to heating of the reagent decreasing its viscosity, which results in higher flow rates and thus a reduced accuracy and precision.

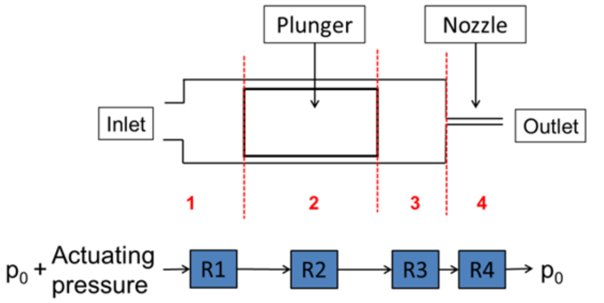

Figure 2: Scheme of the different subsections of the dispensing valve and the corresponding fluidic resistances. The total fluidic resistance equals the sum of the individual resistances R1 to R4.

The fluidic resistances of the various subsections inside the valve are outlined in Fig. 2. Due to the small radius of the nozzle of 100 µm, the total fluidic resistance of the dispensing valve is dominated by the fluidic resistance of the nozzle *R4* [4],

$$R_4 = \frac{8\eta h}{\pi r^4}\,. \qquad (1)$$

Where l and r represent the length and the radius of the nozzle and η represents the viscosity of the reagent. The flow rate q is inversely proportional to the fluidic resistance

$$q \propto (R)^{-1} \propto r^4\,, \qquad (2)$$

which indicates a very strong effect of geometrical tolerances of the radius of the nozzle to the flow rate and therefore to the volumetric dispensing accuracy.

DESIGN

The valve's modular low-cost design consists of "dry parts" which are not in contact with the reagent and "wet parts" which are contaminated by the liquid to be dispensed. The dry parts comprise the actuation solenoid (2.2 Ω, 0.47 mH) and the ring magnet (hard ferrite, 380-400 mT), which functions as a normally closing magnetic attraction mechanism (see Fig. 1, 3 and 4).

The wet parts consist of a metal capillary (ID x h = 0.2 x 5.5 (to 16.5) mm), the valve body and the ferromagnetic plunger (OD x h = 2 x 10 mm, NdFeB, 1170-1250 mT) which is coated with Parylene C to ensure biocompatibility. The metal capillary simultaneously forms the valve seat (upper end) and the nozzle of the valve (lower end). The valve body is fabricated by 3D printing (material "Visijet EX 200") but is designed to be injection-moldable. A circular piece of silicone or EPDM (OD x h = 1.8 x 1 mm) is attached to the lower end of the plunger forming the sealing layer at the valve seat.

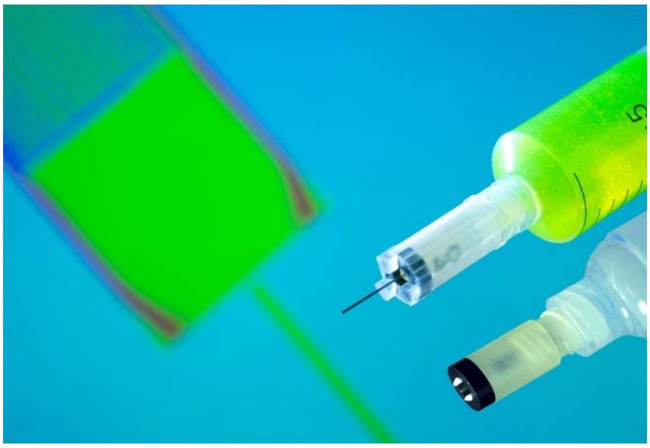

Figure 3: The dispensing valve with its black ring magnet attracting the inner plunger to its normally closed position. Foreground: Two valves mounted on commercial syringes. Upper valve: Long nozzle (16.5 mm) and external ring magnet fixture. Lower valve: Short nozzle (5.5 mm) and ring magnet attached by clamping fixture. Background: A screenshot of numerical simulations of the fluid dynamics within the valve.

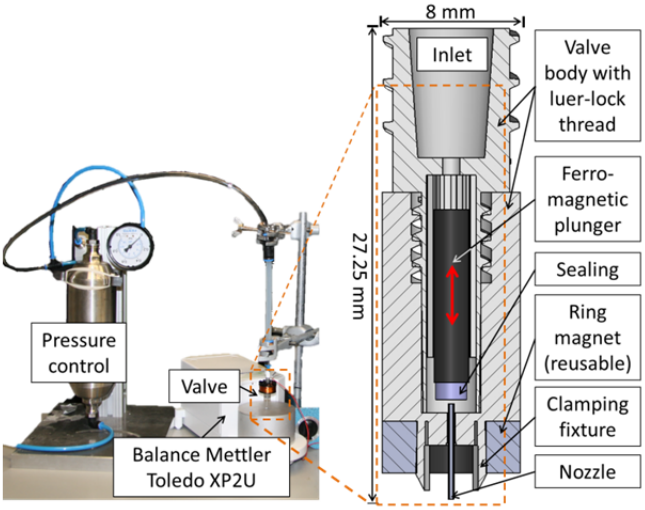

Figure 4: Left: The experimental measurement set-up. Right: Cross-section through the dispensing valve with the movable plunger (red arrow).

EXPERIMENTS

Experiments presented hereafter were performed with a nozzle of the length $h = 5.5$ mm and with EPDM as sealing material. The dispensing performance has been characterized with water (η = 1.03 mPas) and 66% (w/w) glycerol/water solution (η = 16.98 mPas). The actuation pressure was set to 200 – 400 mbar for water and 800 mbar for glycerol to compensate for the higher viscosity. The dispensed volume was measured gravimetrically using an evaporation compensating measurement method as described by Liang et al. [5]. Each data point of Fig. 5

and 6 represents the mean volume $\overline{V}$ of one run of $N = 24$ individually measured aliquots V_n:

$$\overline{V} = \frac{1}{N}\sum_{n=1}^{N} V_n \, . \tag{3}$$

The "*Intra-Run CV*" [6] of the respective run,

$$Intra-Run\ CV = \frac{\sqrt{\frac{1}{N-1}\sum_{n=1}^{N}(V_n-\overline{V})^2}}{\overline{V}}, \tag{4}$$

represents the coefficient of variation (CV) of the volume of N aliquots of a run. The variation across $L = 4$ different dispensing valves was evaluated and is denoted by the "*Tip-to-Tip CV*" defined as [6]:

$$Tip-to-Tip\ CV = \frac{\sqrt{\frac{1}{L-1}\sum_{l=1}^{L}(\overline{V}_l-\overline{V}_{T2T})^2}}{\overline{V}_{T2T}}, \tag{5}$$

Whereby $\overline{V}_l$ represents the mean volume of one run with one valve l and $\overline{V}_{T2T}$ represents the mean volume of all $L = 4$ valves. The *Tip-to-Tip CV* measures the volumetric precision of the different valves' mean volume if all parameters (actuation time and pressure) are kept constant. Thus, it evaluates the influence of the fabrication tolerances, in particular variations of the inner diameter of the nozzle, on the dispensing accuracy of the individual valves.

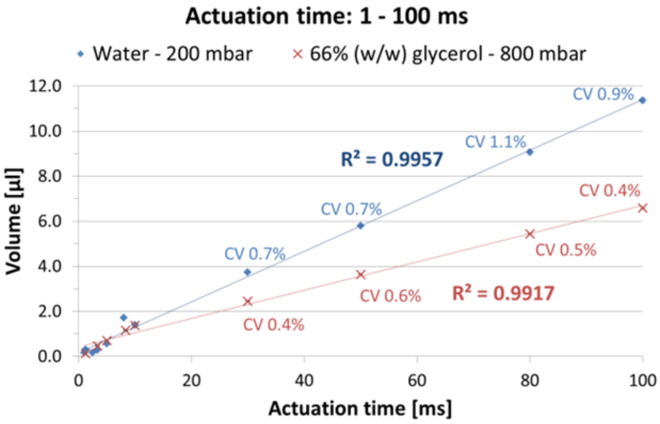

Figure 5: The dispensed volume in dependence of the actuation time for water (blue squares) and glycerol (red crosses). Each data point represents one run of 24 individual measurements. Percentages and corresponding error bars (too small to be visible in this figure) state the respective Intra-Run CV.

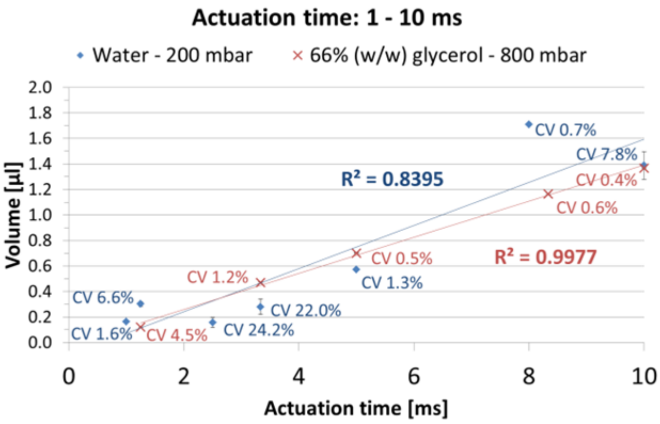

Figure 6: Detail of Fig. 5 for actuation times ≤ 10 ms. The measured minimum volume was 163 nl for water (Inter-Run CV 1.6%) and 123 nl for glycerol (Inter-Run CV 4.5%).

RESULTS

Volume range and linearity

The actuation time of the solenoid was varied between 1 to 100 ms. The measured volume ranged between 163 nl to 11.4 µl for water and 123 nl to 6.6 µl for 66% (w/w) glycerol. The correlation of the measured volume to the actuation time was very linear for the complete volume range with $R^2 = 0.9957$ for water and $R = 0.9917$ for glycerol, as shown in Fig. 5. For very small volumes < 2µl (see Fig. 6) coefficient of determination was $R^2 = 0.8395$ for water and $R^2 = 0.9977$ for glycerol. The flow rate, calculated from the measurements at 100 ms, was 113.61 µl/s (water) and 65.95 µl/s (glycerol).

Intra-Run CV

The dispensing valve showed a highly precise dispensing performance with *Intra-Run CVs* prevalently below 1.0% for volumes > 2 µl (see Fig. 5) and prevalently below 8% for volumes in the range of 0.1 to 2 µl (see Fig. 6 and Tab. 1).

Two outliers in terms of a high *Intra-Run CV* at 280 nl (*Intra-Run CV* = 22.0%) and at 157 nl (*Intra-Run CV* = 24.2%) can be explained by the absence of the very first aliquot for the respective runs i.e. no liquid was ejected in these first dispenses at all.

The *Intra-Run CVs* at the smallest volumes were 1.6% for water at 163 nl and 4.5% for glycerol at 123 nl. Hence, the dispensing valve enables the high precision dispensing of liquid volumes down to the lower end of the sub-µl range.

Tip-to-Tip CV

The *Tip-to-Tip CV* of four different tips was 14.7% or 150 nl (at a mean volume of 1.02 µl, see Tab. 1), revealing considerable variations of the flow rate for different valves due to fabrication tolerances.

Table 1: Tip-to-tip experiments with $L = 4$ different valves. The runs were performed with water at an actuating pressure of 400 mbar with an actuating time of 5 ms. The mean volume of all four valves is 1020 µl with a Tip-to-Tip CV of 14.7%.

	Valve $l = 1$	Valve $l = 2$	Valve $l = 3$	Valve $l = 4$	**T2T CV**
Volume $\bar{V}_l$ [µl]	1.16	1.07	0.83	1.02	**1.02**
Intra-Run CV	1.9%	2.4%	5.7%	2.2%	**14.7%**

The diameter of the used nozzles is specified with fabrication tolerances of ±10 µm. According to equation 2, this corresponds to an expected variation of flow rate in-between $q_{\mathrm{min}} = -18.6\%$ to $q_{\mathrm{max}} = +21.6\%$, which matches well with the experimental *Tip-to-Tip CV* of 14.7%. Thus, the volumetric variation across different valves is mainly attributed to the nozzle. It could be improved e.g. by injection molded nozzles with low tolerances or by individual calibration of each valve.

Variation of nozzle length

For some applications, e.g. for the aspiration of reagents out of micro titer plates, an elongated nozzle length can be necessary. Equations 1 and 2 imply that the flow rate q is expected to be inversely proportional to the nozzle length h. In Tab. 2, the flow rate of water for a nozzle length of $h = 16.5$ mm is compared to a nozzle having a third of the length ($l = 5.5$ mm). The experiments are in good accordance with the theory. Hence, the nozzle length can be changed in order to adapt the flow rate and the functionality of the dispensing valve to specific applications.

Table 2: Experimental evaluation of the flow rate q of water at different nozzle lengths.

	$h = 16.5$ mm	$h = 5.5$ mm
Pressure: 0.2 bar	$q = 48$ µl/s	$q = 125$ µl/s
Pressure: 0.4 bar	$q = 88$ µl/s	$q = 232$ µl/s

It should be noted, that due to the linear increase of the fluidic resistance for a longer nozzle, the required minimal actuating pressure for dispensing high viscous liquids increases also. For 66% (w/w) glycerol solution the minimal actuating pressure increased from 0.7 to 1.3 bar when the nozzle length was increased from 5.5 mm to 16.5 mm.

CONCLUSION

We have presented a normally closed, non-contact, solenoid dispensing valve for the sub-µl range. The *Intra-Run CV* primarily was below 1% for volumes > 2µl and below 8% for volumes in the range of 0.1 to 2 µl. The *Tip-to-Tip CV* was 14.7% at 1.0 µl indicating a strong influence of fabrication tolerances on the flow rate of the valve and the necessity to calibrate the valve for a specific application.

Its modular injection moldable design allows for low-cost fabrication and disposable use of all liquid contaminated components. Thus, elaborate washing procedures are obsolete and cross-contamination is prevented effectively. Its compact design (8 x 27.25 mm) and the standard Luer-Lock interface enable straightforward micro dispensing with high precision up to the sub-µl range.

REFERENCES

[1] D. A. Dunn, I. Feygin, Challenges and solutions to ultra-high-throughput screening assay miniaturization: submicroliter fluid handling, *Drug Discovery Today,* vol. 5, pp. 84-91, 2000

[2] W. D. Niles, P. J. Coassin, Piezo- and solenoid valve-based liquid dispensing for miniaturized assays, *Assay and Drug Development Technologies,* vol. 3, pp. 189-202, 2005

[3] K. Fanwei, Y. F. Zheng, C. Weidong, Automatic liquid handling for life sciences - A critical review of the current state-of-the-art, *International Conference on Robotics and Biomimetics,* pp. 480-486, 2009

[4] Encyclopedia of Microfluidics and Nanofluidics, *Springer,* 2008,

[5] D. Liang, C. Steinert, S. Bammesberger, L. Tanguy, A. Ernst, R. Zengerle, P. Koltay, Novel gravimetric measurement technique for quantitative volume calibration in the sub-microliter range, *Journal of Measurement Science and Technology (submitted),* 2012

[6] S. Bammesberger, A. Ernst, N. Losleben, L. Tanguy, R. Zengerle, P. Koltay, Quantitative characterization of non-contact microdispensing technologies for the sub-microliter range, *Drug Discovery Today (submitted),* 2012

CONTACT

*S.Bammesberger, stefan.bammesberger@imtek.de