SIMULATION STUDY OF A NOVEL CAPACITIVE PRESSURE SENSOR CONCEPT BASED ON THE GEOMETRICAL DEFORMATION OF AN ELASTIC MEASURING CELL

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ABSTRACT

We present the simulative investigation of design rules for a novel pressure transducer to realize a disposable pressure sensor for medical applications. The presented simulation study is based on a three-dimensional CFD-ACE+ model, which describes the expansion behavior of tubular, elastic measuring cells at varying inner hydrostatic pressures for and different boundary conditions like material properties or size. The elastic measuring cell is exposed to an electric field which is sensitive to the implied geometrical deformation, thus transduces a pressure change to a change in capacitance.

KEYWORDS

Disposable pressure sensor, capacitive sensor, CFD-ACE+ model, medical

INTRODUCTION

In general, pressure sensors have a wide range of applications, for example in the petrochemical industry, automotive industry, consumer electronics, process technology and in medical industry. Medical applications particularly require disposable low-cost pressure sensors. They are used for monitoring infusion systems or blood pressure measurements, but also in the in vitro diagnostics (IVD) pressure sensors are applied for monitoring the dispensing process and providing qualitative information back to the system whether the process was successful or not. Standard IVD test systems are based on mechanically operated pipetting systems, which are controlled by robotic arms without sensor feedback. Significant disadvantages of these systems are the large size, the risk of cross-contamination, the costly cleaning steps of the pipette tips, and the large volume of liquid that is applied per test. In order to improve these systems, we want to combine a disposable, non-contact dispensing valve, like [1], with the presented low-cost pressure sensor. Non-contact dispensing systems are able to dispense smaller volume in a shorter process time and avoid cross contamination. A particular advantage of disposable dispensing systems is the lack of necessity of time and cost consuming washing steps. The demand for reliable and inexpensive sensors is rapidly increasing pushing the development of new technologies, especially based on micro- and nanotechnology [2, 3].

Most commercially available pressure sensors are based on the piezoresistive measuring principle [2]. The novelty of the presented sensor approach is the contactless capacitive measurement of the deformation of an elastic measurement cell which depends on the change of the inner hydrodynamic or hydrostatic pressure inside the cell. The sensor is designed for the measurement of liquid pressures, whereas the liquid itself acts at dielectric. All liquid contaminated parts can be disposed, whereas the expensive amplification electronics and electrodes can be used again. In contrast to prior art capacitive sensors, the measuring principle is based on a change in the amount and distribution of the dielectric in the sensor. Standard capacitive sensor concepts are based on the change of the distance of two or more electrodes relative to each other. In this concept, it is difficult to separate the electronics from the fluid-carrying components.

WORKING PRINCIPLE

The presented work introduces a novel concept of a low-cost pressure sensor where a pressure change is measured by a change in capacitance due to the deformation of an elastic measuring cell, cf. fig. 1.

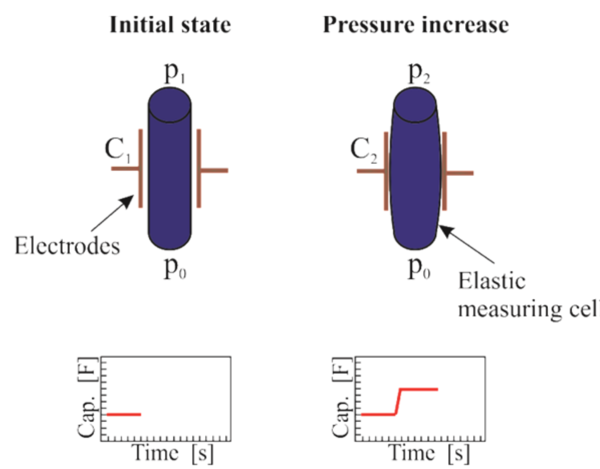

Figure 1: Schematic sketch of two states of the disposable capacitive pressure sensor comprising an elastic measuring cell mounted between two electrodes and filled with a medium acting as dielectric material (initial state). A pressure increase results in an expansion of the cell and therefore in a change of capacity.

The desired modular construction of the

disposable micro-dosing system should consist of a disposable dispensing valve and low-cost pressure sensor integrated in the fluid path between the reservoir and the valve. The sensor is illustrated in figure 1 consisting of a cell, presented as a tube shaped cell, which is mounted concentrically between two electrodes by local fixations on the inlet and outlet side. The cell is connected to the fluid line which is focused to be measured, thus filled with the medium of interest acting as dielectric material. An applied hydrodynamic pressure for an open outlet or an applied hydrostatic pressure for a closed outlet results in geometrical deformation of the elastic measuring cell which implies a change in capacitance of the electrode arrangement due to the increasing amount and the change of distribution of dielectric material in the electric field. Thus, a maximum growth in the cell's diameter at a certain pressure increase implements maximum sensitivity.

THERORETICAL INVESTIGATION

The theoretical investigation focuses of the expansion behavior depending on the applied inner hydrostatic pressure of the tubular, elastic measuring cell. CFD-ACE+ is applied as simulation tool to identify design rules for an enhanced sensitivity considering certain boundary conditions. Especially the influence of the cell's length - distance in-between the fixation - and the young's modulus of the cell material were in focus. The influence of the length in the range from 1.5 to 5 mm and a variable Young's modulus in the range of 1 MPa to 12 MPa were investigated at different applied pressures from 0 to 1 bar.

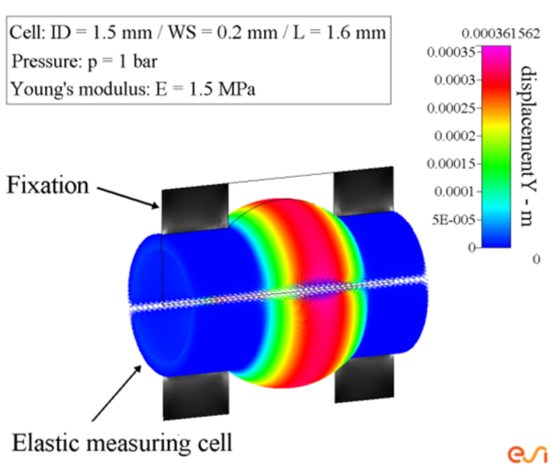

Figure 2: Illustration of the three-dimensional CFD-ACE+ simulation result for an elastic, tubular measuring cell at an inner hydrostatic pressure of 1 bar (Type A (see table 1), L = 1.6 mm).

As a boundary condition of the simulation it is determined that the flexible measuring cell is firmly clamped at both ends, where on one side the pressure is applied and the other is closed. For the material of the measuring cell, we assumed linear material properties and a constant Young's modulus.

RESULTS OF THE THEORETICAL INVESTIGATION

Influence of the Young's modulus

Here, the influence of the young's modulus on the expansion behavior was investigated. Therefore, the Young's modulus for flexible round measuring cells with a fixed geometry was varied between 1 and 14 MPa. The inner hydrostatic pressure was increased in steps of 50 mbar from 0 to 1 bar and the change of the maximal outer diameter of the arched-shaped expansion profile of the measuring cell is plotted. The change of the maximal outer diameter in correlation to the applied pressure shows a linear dependency for the assumption of a linear Young's modulus and material properties.

In order to illustrate the dependency of the material properties, the maximal displacement per applied pressure (slope in µm/bar) was plotted against the Young's modulus (cf. fig. 3). The simulation study revealed an allometric relationship between the Young's modulus and the cell expansion at constant hydrodynamic pressure. Therefore for maximum sensitivity, a cell material with low Young's modulus is preferred.

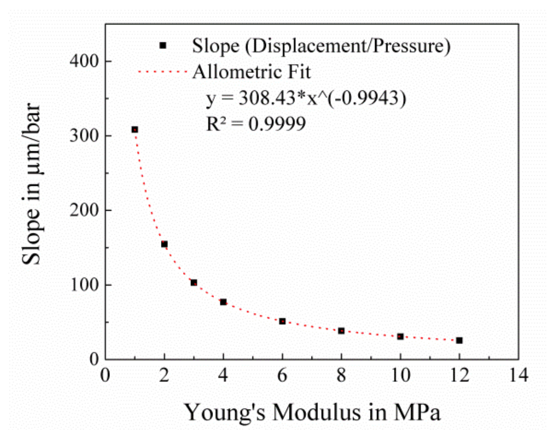

Figure 3: The change of the maximal outer diameter per applied pressure (slope) is plotted in dependency of the Young's Modulus for cell type A with a length of 1.6 mm.

Influence of the length of the measuring cell

Also, the influence of the length on the expansion behavior was examined. The comparison of different lengths showed increase of maximal expansion for longer measuring cells. It was found that the maximal expansion per applied pressure of the measuring cell converges for increasing tube lengths to a maximum change in an asymptotic manner (cf. fig. 4). For a cell length > 4 mm, the influence of the length is negligible because the expansion profile shows a plateau for longer cells.

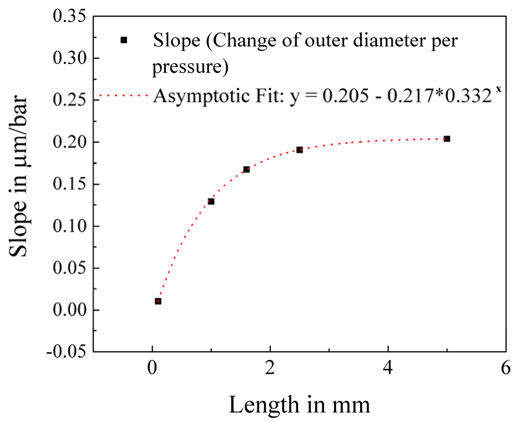

Figure 4: The change of the outer diameter in µm in correlation to the applied pressure in mbar (slope) shows a linear dependency. The slope converges for increasing tube lengths to a maximum change in an asymptotic manner. Here, plotted for cell type C.

Influence of inner diameter and wall thickness

The variation of inner diameter (ID) to wall thickness (WS) ratio showed that the expansion increases, the greater the ID / WS ratio at constant ID. In addition, the expansion increases at a constant ID / WS ratio, the larger the inner diameter is. For a high sensitivity - maximal expansion per applied pressure - we are searching for a measuring cell with a big ID, combined with large ID / WS ratio. The influence of the ID / WS ratio should also be validated experimentally.

EXPERIMENTAL SET-UP

Three different commercially available silicone rubber tubes were selected (see table 1) to emulate the simulation model of the elastic measuring cell by experiment.

Table1: Variants of the tubular measuring cell made of silicone rubber used for experimental validation. The Young's modulus was determined experimentally.

Type	Inner diameter	Wall thickness	Young's modulus
A	1.5±0.1 mm	0.2±0.1 mm	3.85 MPa
B	1.9±0.03	0.1±0.03 mm	4.64 MPa
C	2.5±0.1 mm	0.2±0.1 mm	3.62 MPa

The experimental characterization of the change of the outer diameter of the tube per applied hydrostatic pressure was realized by the laser scan micrometer optoCONTROL 2600 from MICRO-EPSILON featuring a geometrical resolution of 0.6 µm (cf. fig. 5). The both sided clamped silicone tube is left pressurized by a pressure control valve from FESTO and has a dead end at the right. The tube and its holder are mounted on a stepper motor and are placed inside the laser scan micrometer. The outer diameter was measured at eight different position 0 to 7 distributed evenly over the entire length of the tube. Position 0 and 7 are located at the beginning and end of the tube respectively. The pressure and the movement of the stepper motor were controlled via software.

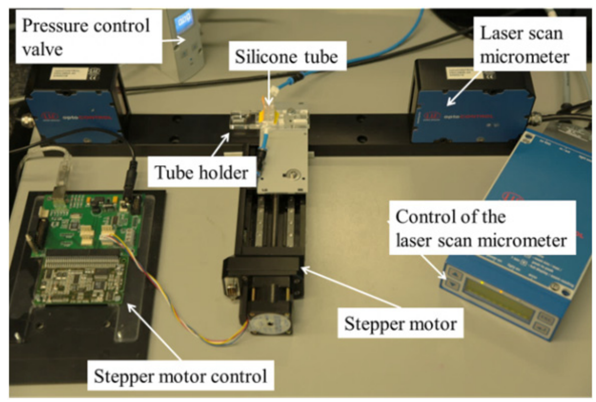

Figure 5: Illustration of the experimental set-up, with a laser scan micrometer of the company MicroEPSILON, a stepper motor, control electronics of the stepper motor and the pressure control valve. Not shown is the control electronic of the pressure control valve and the control software.

In order to experimentally determine the reproducibility of the expansion behavior, we increased the inner hydrostatic pressure from 0 bar to a defined target pressure following a specific measuring loop as illustrated in figure 6. The defined target pressures are set to: 250 mbar, 500 mbar, 750 mbar and 1000 mbar. At the beginning of the loop, the pressure is set to 0 bar and the outer diameter is measured at position 0 to 7. The first pressure increase to a certain target pressure is again followed by the measurement of the outer diameter as described above. The pressure change from 0 bar to the target pressure is repeated six times (cf. fig. 6). This measurement loop for one target pressure is then repeated for the other set of target pressures. Successively, we repeated the loop five times to verify the permanent elasticity and reproducibility of the deformation behavior. After that, the complete loop is performed with two other tubes of the same geometry.

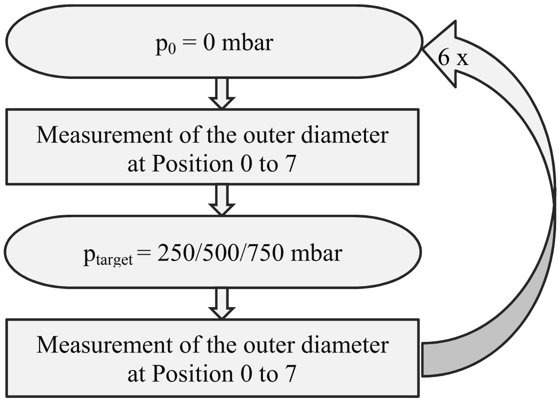

Figure 6: Schematic representation of a measuring loop for the experimental determination of the reproducibility of the expansion behavior of an elastic measuring cell.

EXPERIMENTAL RESULTS

The gained experimental results are depicted in figure 8 showing the results of all three tubular measuring cell types with the length 5 mm in comparison with the simulation results. In order to compare the simulation and the experimental results, we take the mean outer diameter over position 2 to 5 and not the maximal outer diameter. An individual data point represents the mean of the individual changes in outer diameter of position 2 to 5 of three different tubes. The error bars correspond to the standard deviation of a complete measuring loop.

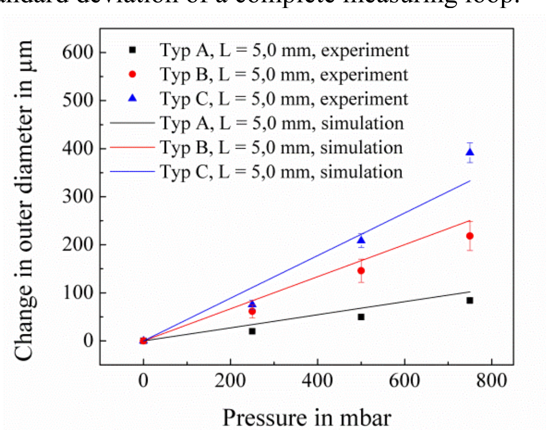

Figure 7: Experimental validation of the simulated expansion behavior of the elastic, tubular measuring cell for three different silicone tubes.

The evaluation showed that the tube type C showed the highest sensitivity with an outer diameter increase of 17.3% at a pressure of 1 bar, where type A only increases by 5.2% and type B by 9.8%. All tube types do not show a linear expansion behavior like the simulation. The deviation of the simulation results from the experimental values can be explained by the non-linear stress/stain behavior of silicone. The biggest difference between the simulation and the experiment exists for of type C, length 5.0 mm, at 500 mbar. Here, the experimentally determined value of the change in outer diameter is 64 µm (27%) bigger than the simulated value. The error bars for applied inner hydrodynamic pressures above 500 mbar are higher, because silicone shows a viscoelastic behavior. The viscoelasticity is characterized by a partially elastic, partially viscous behavior. In figure 8 a measured cyclic stress/strain curve is plotted, where we applied a hydrodynamic pressure and the released it in 250 mbar steps from 0 to 750 mbar.

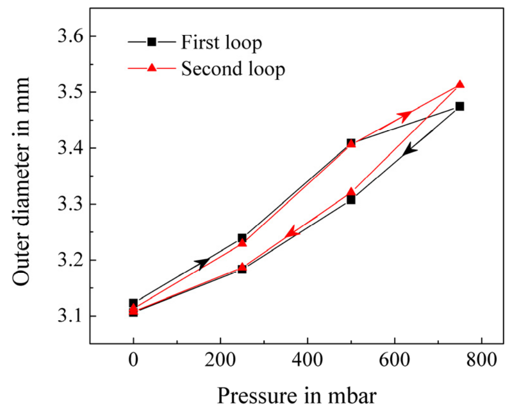

Figure 8: Cyclic load and unloading of tube type C for a pressure range between 0 and 750 mbar.

SUMMARY

In summary, we successfully implemented a model to approximate the expansion behavior of tubular ideal linear measuring cells. Optimized design rules were defined and verified by experiment. In future work, we will extent the model by the implementation of the non-linear viscoelastic behavior and add electrodes to the described model to enable the simulation of the change in capacitance caused by deformation of the measuring cell.

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