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A capillary manometer for pressure measurements in small cavities

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ABSTRACT

Measuring pressures inside small cavities is a demanding task, but an essential one for applications in microfluidics. Although several MEMS-based pressure sensors have already been demonstrated, their fabrication is complicated and they usually require external electronics, making their use onerous. In this paper we propose a simple, home-built, pressure sensor, based on a thin glass capillary. It is in its essence a gas manometer, where the position of a liquid plug inside a capillary, sealed at one end, is correlated with the pressure at the open end. By calibrating in a vacuum chamber, we achieved a pressure uncertainty of less than 10 mbar. The suitability of the sensor for characterizing polydimethylsiloxane (PDMS) pumps was tested by measuring air diffusion through PDMS rings. Permeability and diffusivity were determined from comparison to the numerical model, based on the finite-difference method (FDM). Their values at 25 °C were found to be 2.5×10^{-6} cm^2/s and 1.4×10^{-5} cm^2/s, respectively. Although the lifetime of this type of capillary manometer is limited by the evaporation of the liquid plug at low pressures, its small probe size and simple preparation make it a convenient and relatively accurate sensor to quickly measure the pressure in small cavities.

1. Introduction

The development of pressure sensors with a small probe size is of great importance for characterizing liquid flows in microfluidics, i.e., for the case of degas-driven flow [1–4]. In such a device a polydimethylsiloxane PDMS slab with a network of channels and a pumping cavity is degassed before use. After exposure of the slab to the air, the latter will fill the microfluidic network. Due to the high gas solubility in the PDMS, the air from the microfluidic network is absorbed into the PDMS slab. The resulting reduced pressure induces liquid flow from the inlet opening into the microfluidic network. Since different applications require specific flow rates, an important characteristic of such a pump is the tunability of the flow rate. This can be achieved by changing the geometry of the PDMS slab, its total volume or evacuation time (vacuum exposure) [3]. A change of each of these parameters will affect the flow rate [1].

Due to the importance of a reliable flow-rate control, a method for characterizing PDMS micropumps is required. There are some MEMS-based sensors that can be used [5,6]. Pirani gauges [7] can measure the heat transfer in ambient gas, while some sensors rely on the swelling of the PDMS microchannels due to the excess pressure. In the latter case the pressure is calculated by measuring the change in capacitance of parallel conductive membranes [6], by measuring the resistance of a conductive segment of microchannel walls [8], or by a laser deflection [9]. These methods require external equipment, which can be cumbersome and expensive. In a simpler method [3], the pressure of the micropump is reflected in the hydrostatic pressure of the liquid column [3]. The hydrostatic pressure is simply measured by the displacement of a liquid column. However, even here the measuring system is relatively large.

We propose a simple, quick and reliable method for measuring the pressure in a small cavity. The proposed sensor is independent of any external electronic component, control or power supply. The capillary manometer is shown in Fig. 1. It is composed of a long capillary that is sealed at one end, and contains a liquid plug.

The operation of such a manometer relies on the fact that, at equilibrium, the pressure on one side of the plug is equal to the pressure on the other side. The pressure at the open end of the capillary p is thus directly correlated to the volume of air between the sealed end and the plug V, the number of gas molecules N and the gas temperature T. It follows from the ideal gas law $pV = nk_BT$, where k_B is the Boltzmann constant. If the temperature is kept

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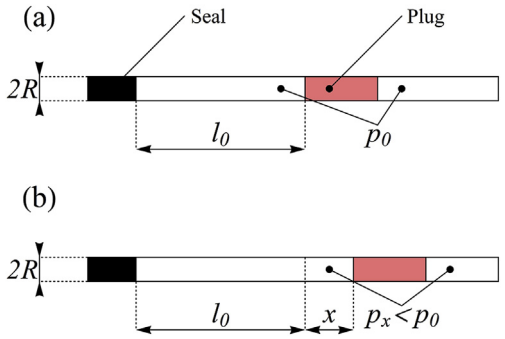

Fig. 1. Pressure at the open end of the capillary is inversely proportional to the volume between the sealed end and the liquid plug. Distance between sealed end and liquid plug is l_0 at atmospheric pressure p_0 (a) and l_0+x at pressure p_x (b).

constant, pV is then constant as well. Assuming a constant inner radius of the capillary R, the volume can be rewritten as $V = \pi R^2 l$, where l is the distance between the sealed end and the liquid plug. If at atmospheric pressure p_0 the distance l_0 is measured, it follows that $p_0 l_0 = pl = p(l_0+x)$, when the temperature T, inner radius R and number N are assumed to be constant. The manometer's response is then described as

$$p(x) = \frac{p_0 l_0}{l_0 + x} \tag{1}$$

and the constant l_0 can be measured during exposure of the open end to atmospheric pressure, or can be determined in another similar calibration step.

The open end of the capillary manometer can be inserted into a micro cavity, ensuring a small probe size (volume of the capillary) with minimum influence on the measuring system. Furthermore, the position of the liquid plug can be observed with the naked eye or with a camera, thus eliminating the need for external power to the sensor.

2. Materials and methods

We have used several glass capillaries with different inner diameters in the range from 0.2 mm to 0.4 mm. Capillaries were cut to lengths of about 20 cm. Eq. (1) requires a constant diameter, but in our case, there was a maximum 20 μm difference over the length of 20 cm for each capillary. The nonuniformity was mainly in a shape of a straight taper, as estimated from the measurement of the outside diameter. Variation of the capillary radius of 10% over its length would lead to a quite large measurement uncertainty (see Appendix), so we decided to calibrate a length-to-pressure scale for each capillary separately. The capillaries were cleaned with ethanol and dried with a pure nitrogen gas.

The choice of liquid to be used as a plug is very important. Its vapour pressure must be low, in order to decrease the evaporation of the plug when working at low pressures. At first, mercury was chosen for the plug, due to its low vapour pressure and high visibility. Its movement, however, was found to be discontinuous, due to its high surface tension. Oil, commonly used in oil manometers, was discarded, because it sticks to the glass walls of the capillary. Finally, de-ionized water was tested and, when coloured with food dye for visibility, proved to be very reliable. Its only drawback is its high vapour pressure and the subsequent evaporation of the plug, when working at pressures below atmospheric (up to 2 mm per day at 500 mbar). This limits the lifetime of the capillary manometer. Fortunately this continuous evaporation takes place only at the open end of the capillary. The sealed part of the capillary is quickly filled with the saturation pressure of the liquid so the evaporation does not affect the volume of the sealed part.

A drop of coloured de-ionized water was injected into each capillary, forming a liquid plug of about 1 cm. The plug was positioned at a distance l_0 from the end of the capillaries, which were then sealed over a flame. The distance l_0 was chosen to be as large as possible, since the precision of the measured pressure is proportional to it. Capillaries were then taped onto a measuring scale made by printing line marks on a paper, with major and minor marks spaced at 1 mm and 0.2 mm, respectively. Capillaries with measuring scales were placed into a pressure-calibration chamber to be inspected for possible hysteresis and discontinuous plug behaviour. If satisfactory, the capillaries were placed into a mould for a PDMS ring.

The PDMS (Sylgard 184, Dow Corning) was prepared according to the manufacturer's instructions, by mixing the base and the curing agent in a 9:1 wt ratio. The mixture was degassed in a vacuum chamber for half an hour in order to remove the trapped air bubbles. The mixture was then poured into moulds with the capillaries and left to cure for 24 h. Once solidified, the PDMS rings were carefully separated from the moulds and placed on a glass support plate, and the capillaries were aligned with the measuring scale. An assembled device is shown in Fig. 2 (a).

The rings were exposed to air during the PDMS solidification, and were therefore saturated with air after the assembly. All the experiments described in this paper were performed with environmental air.

The devices were then placed in a stainless-steel vacuum chamber, in which the desired gas pressure from 1000 mbar to 1500 mbar can be set and measured with a high-precision absolute pressure gauge (DH Instruments RPM3, uncertainty 0.01% of measured value). The pressure inside the chamber was then slowly lowered (or raised) to the desired value of 500 mbar (or 1500 mbar). Meanwhile, the displacement x was measured on the measuring scale at several intermediate pressure values with an optical microscope. After reaching the lowest/highest pressure the inverted measurement was made, bringing the pressure back to atmospheric pressure to check for any potential hysteresis. This procedure resulted in a “length-to-pressure” calibration curve for each capillary. The initial position l_0 to be used in Eq. (1) was then precisely determined using the method of least squares.

After the calibration, the devices were taken out of the vacuum chamber and the PDMS rings were covered with a glass cover plate to seal the cavity under atmospheric pressure, as shown in Fig. 2

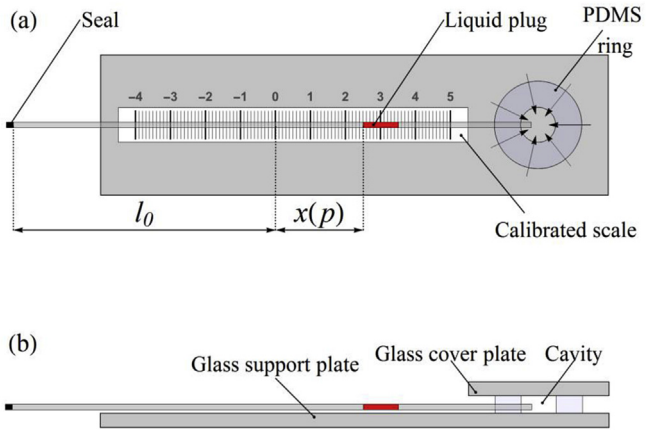

Fig. 2. PDMS ring with an embedded capillary manometer on a glass support plate with a measuring scale. Top view of the open device with arrows representing air diffusion (a) and cross-section view of the device, closed with a glass cover plate (b).