Whitepaper measurement of flow resistivity

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Introduction

The concept of flow resistance, also called hydrodynamic resistance or just microfluidic resistance, corresponds to the opposition that a fluidic element, like a channel, offers to a flow through it. Each element of a microfluidic circuit offers some resistance to the flow, which is translated into a pressure drop of the total system. Flow resistance is clearly one of the most important concepts to consider while designing a microfluidic circuit as it affects the operation conditions of the system. The calculation of the flow resistance of microfluidic devices is less accurate then of macroscale devices because the theoretical set of equations may not represent the reality; complex fluid paths, interaction with channel walls can be variables of influence and are difficult to model. In addition to that, it is likely that in parallel channel arrangement, the fluid does not always make a predictable flow distribution among the branches. This all leads to situations for which the theoretical set of equations will not represent the reality.

Finally, accurate measurements of flow resistivity can help to get more fundamental understanding of the performance of the microfluidic device and can help to improve the design and/or providing opportunities for other applications.

Definitions

For practical purposes we divided the range of flow rates used in microfluidics into three subranges. Most of the microfluidic devices operate in the middle flow rate range. The general use of several calibration methods and the flow rates for each of these groups are described in the following table. Flow range distribution is based on the uncertainty achieved and the general calibration method used.

Table 1: Resume of methods and flow rates

Flow rate	**Calibration method**	**National metrology standards (best calibration uncertainty)**	**Specified accuracy commercial sensor (I)**	**Specified accuracy commercial sensor (II)**
Low flow rate: 1 nl/min to 1 µl/min	optical methods preferably, or low-flow displacement methods in general	around 1% in general	10% (200 nl/min - 1.5 µl/min)	2% FS (83 nl/min-33 µl/min)
Middle flow rate: 1 µl/min to 100 µl/min (hot spot)	gravimetric or displacement methods	around 0.5% in general	5% (6 µl/min - 110 µl/min)	0.2%Rd (0.83 µl/min-3.3 ml/min)
High flow rate: 100 µl/min to 10 ml/min	gravimetric methods	around 0.1% in general	5% (1.2 ml/min – 8 ml/min)	0.2%Rd (16.7 µl/min-33.3 ml/min)

II. Flow versus pressure difference

a. Description of the test

Flow resistivity measurement is used to determine the necessary pressure to achieve the desired flow through a microfluidic circuit, or conversely, to determine the flow rate corresponding to a given inlet pressure. Flow resistivity measurement consists of measuring the differential pressure (or solely the inlet pressure if the outlet is at atmospheric pressure) of a given microfluidic circuit and measuring the flow passing through the same microfluidic circuit, either simultaneously or sequentially, for at least one (preferably several) combinations of flow rates and pressure. The flow resistivity can be given in Pa.s/m^3.

b. Measurand

The pressure drop according to the desired flow rate in the flow system can be calculated by using the Hagen-Poiseuille equation:

$$\Delta P = QR_H \tag{2.1}$$

Where ΔP is the pressure difference, or drop, between two points of the system, Q is the flow rate and R_H is the hydraulic resistance.

It can be demonstrated that the pressure drop associated with any section of a microchannel depends on the flow rate, the dimensions of the channel and the dynamic viscosity of the fluid itself. The flow resistor expressions for the most typical channel cross sections are as follows. These are, respectively: circle, rectangle, and square shapes:

$$R_{Hc} = \frac{8\mu L}{\pi r^4} \qquad R_{H,rec} = \frac{12\mu L}{1-0{,}63\left(\frac{h}{w}\right)}\left(\frac{1}{h^3 w}\right) \qquad R_{H,sq} = \frac{12\mu L}{1-0{,}917\times 0{,}63}\left(\frac{1}{h^4}\right) \tag{2.2}$$

Where:

r is the radius of the circle.

μ is the dynamic viscosity.

L, h, w the length, height, and width of the channel.

The assumptions for this theoretical model are the following:

- small Reynolds number,
- incompressible fluid,
- unidirectional flow,
- steady flow along the channel,
- small fluid mass per distance unit, so gravity is negligible.

d. Test method

Measuring flow resistivity across a microfluidic device is performed using at least a pressure source (pressure controller in the figures below, which includes a pressure source to stabilize and control the pressure, such as a control valve), a flow sensor, and either:

- one pressure sensor at the device's inlet, the outlet being at atmospheric pressure, as shown in the following schematic:

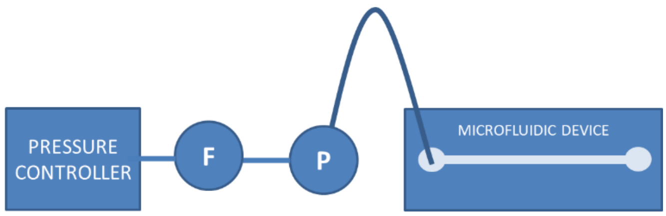

Figure 1: One pressure sensor

- one differential pressure sensor in parallel of the microfluidic device, as shown in the following schematic:

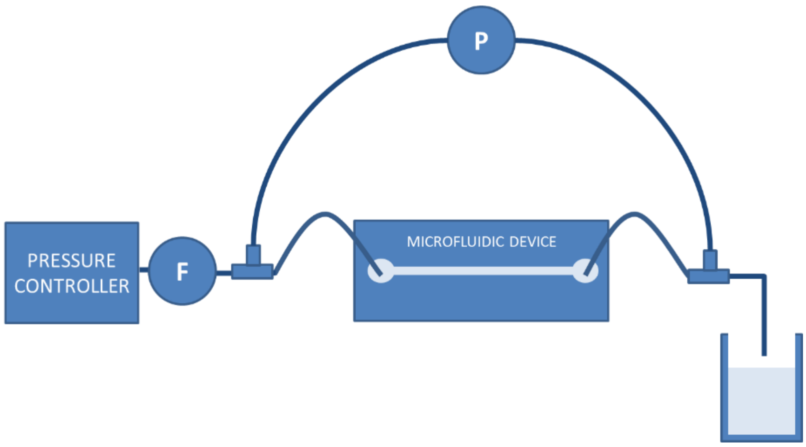

Figure 2: One differential sensor

- two pressure sensors at inlet and outlet of the microfluidic device, as shown in the following schematic:

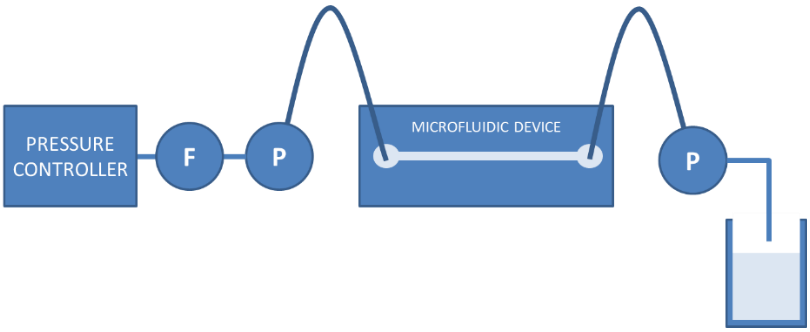

Figure 3: Two pressure sensors

e. Set up and test equipment

In the three schematics above, the specifications are:

- Pressure controller:
    - It must be chosen according to the admissible pressure range in the microfluidic device. Generally, a pressure controller should be used between 10% and 100% of its pressure range capability.
    - Minimum pressure at the outlet of the pressure controller is generally around 100 mbar in order to ensure good pressure control and stability.
    - The stability of the pressure controller must be in accordance with the accuracy required for the pressure drop / flow resistivity measurement. This information can be found in the datasheet of the pressure controller. Note that the stability can be degraded due to the compliance (elasticity) of the entire setup and dead volumes which can entrap air (in case of a liquid as the test media).
    - A sufficient pressure level at the pressure source (inlet) of the pressure controller should be provided in order to perform in a nominal way. The minimum and maximum pressure level can be found in the datasheet of the pressure controller. The same applies for the required electrical power supply.
    - The pressure controller should be at the same altitude as the microfluidic device.

- Pressure sensor(s), differential pressure sensors:
    - It must be chosen according to the pressure range (or pressure drop range in case of a differential pressure sensor) to be measured in the microfluidic device. Generally, a pressure sensor should be used between 10% and 100% of its pressure range capability.
    - The accuracy of the pressure sensor must be in accordance with the accuracy required for the pressure drop / flow resistivity measurement. This information can be found in the datasheet of the pressure sensor. Note that this accuracy can be degraded due to the compliance (elasticity) of the entire setup and dead volumes which can entrap air (in case of a liquid as the test media).
    - The pressure sensor(s) should be at the same altitude as the microfluidic device.
    - All pressure sensors should be calibrated before any pressure measurements.
    - In case of a liquid as the test media, the tubing connecting the pressure sensor(s) to the pressure controller and microfluidic device should be set downward so that air bubbles are expelled (purged) downstream of the setup.
    - In case of a gas as the test media, the tubing connecting the pressure sensor(s) to the pressure controller and microfluidic device should be set upward so that liquid droplets (due for example to condensation of humidity) are expelled (purged) downstream of the setup.

- Flow sensor:
    - It must be chosen according to the flow range to be measured in the microfluidic device. Generally, a flow sensor should be used between 10% and 100% of its pressure range capability.
    - The accuracy of the flow sensor must be in accordance with the accuracy required for the pressure drop / flow resistivity measurement. This information can be found in the datasheet of the flow sensor. Note that this accuracy can be degraded

due to the compliance (elasticity) of the entire setup and dead volumes which can entrap air (in case of a liquid as the test media).
    - All flow sensors should be calibrated before any pressure measurements.
    - In case of a liquid as the test media, the tubing connecting the flow sensor(s) to the pressure controller and microfluidic device should be set downward so that air bubbles are expelled (purged) downstream of the setup.
    - In case of a gas as the test media, the tubing connecting the flow sensor(s) to the pressure controller and microfluidic device should be set upward so that liquid droplets (due for example to condensation of humidity) are expelled (purged) downstream of the setup.

- Fittings/connectors:

    - All fittings and connectors should be chosen and set keeping in mind that any leakage will cause measurement error and will decrease the flow resistivity accuracy.
    - All fittings and connectors should be chosen as to minimize their dead volume.

g. Test conditions

Measurements should be performed in a temperature and humidity-controlled room. Temperature, ambient pressure, and humidity fluctuations range should be known, either by measurement (using calibrated sensors) or by knowledge of the control ranges, ensuring that the climate-control system (air-conditioning for example) is performing normally. Ideal conditions are 23+/- 2 °C and 55+/-5%HR.

h. Preparation

All elements of the setup (pressure controller, measurements sensors, test media, and microfluidic devices) should be left in the room where the tests are to be performed at least 24 hours before the test, to ensure thermal equilibrium. Electrically powered elements such as the pressure controller and the pressure sensor(s) should be powered on at least 30 minutes before beginning any measurement. For pressure controllers requiring the filling of a reservoir, the latter should be filled beforehand, at least 30 minutes before beginning any measurement. The entire system, including pressure taps in case of differential pressure sensor, should be purged before beginning any measurement. Purge can be performed using the test media at the maximum admissible pressure of the pressure controller/pressure sensor(s)/microfluidic device (whichever has the lesser maximum admissible pressure).

i. Test procedure

Keeping in mind the requirements stated above:

1. Dispose of all setup elements in the room where the tests are to be performed, for at least 24 hours before beginning any measurement.
2. Connect all elements together to mount the setup, making sure that all fittings are tightly connected.
3. If necessary, fill the pressure controller reservoir at least 30 minutes before beginning any measurement.
4. Connect all required electrical power supplies to the pressure controller and pressure sensor(s), and power on at least 30 minutes before beginning any measurement.
5. Purge the setup using the test media at the maximum admissible pressure of the pressure controller/pressure sensor(s)/microfluidic device (whichever has the lesser maximum admissible pressure).
6. Zero the pressure and flow sensors to minimize any measurement offset.
7. Set a target pressure to the pressure controller and monitor the evolution of the pressure using the pressure sensor(s).
8. After reaching a stable pressure (not drifting upwards of downwards), record the measurement.
9. Repeat step 7 and 8 for all required target pressure.
10. In case of a differential pressure sensor or two pressure sensors, remove the microfluidic device and connect directly both pressure taps in order to measure the pressure taps pressure drops. Repeat step Repeat step 7 and 8 for all measured flows in the previous steps.
11. Calculate each flow resistivity according to equation (2.1). In case of a differential pressure sensor or two pressure sensors, subtract the pressure taps pressure drops to the calculated device's pressure drop.
12. An example of flow and pressure drop measurement is shown in the figure below, for 4 different flow and pressure measurements steps.

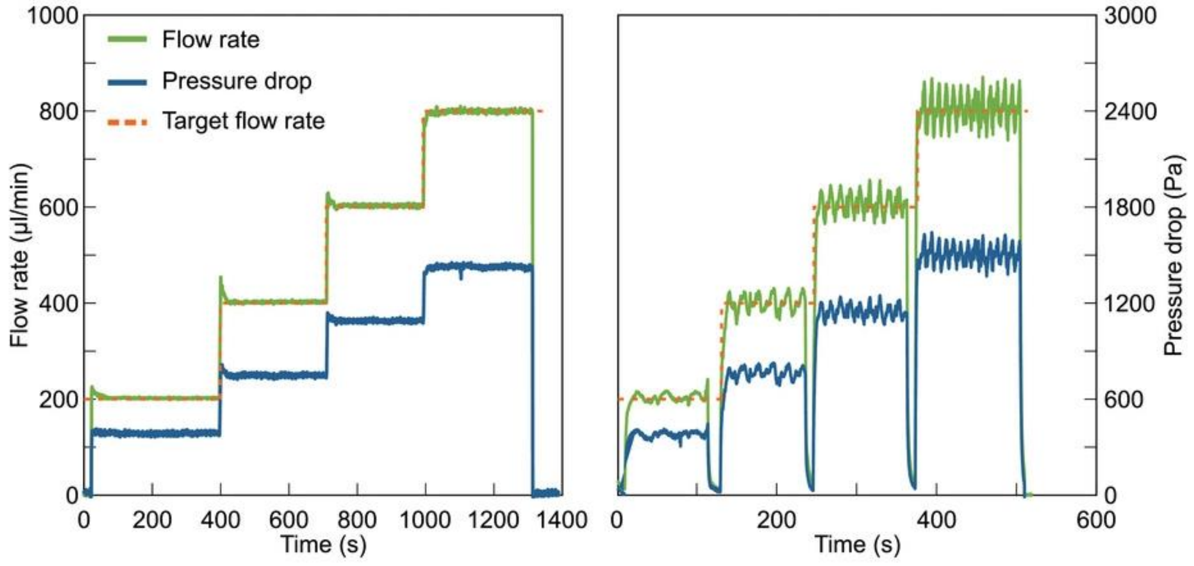

Figure 4: pressure drop and flow rate measurements [1]

III. Dry evaluation of flow resistivity

Dry calibration consists in using the dimensional measurement of the microfluidic device to calculate its flow resistivity. If possible, all needed dimensions should be measured using a calibrated instruments with a measurement resolution and accuracy in agreement with the target measurement uncertainty.

Examples of dry evaluation of flow resistivity are given in:

https://www.elveflow.com/microfluidic-reviews/general-microfluidics/flow-resistance/

https://en.wikibooks.org/wiki/Microfluidics/Hydraulic_resistance_and_capacity

Recommended further reading:

General reading

Christopher Vega-Sánchez,Chiara Neto, Pressure Drop Measurements in Microfluidic Devices: A Review on the Accurate Quantification of Interfacial Slip, Advanced Materials Interfaces, Volume 9, Issue 5, February 14, 2022

Specific reading on flow measurement:

Whitepaper Flow measurement of microfluidic devices