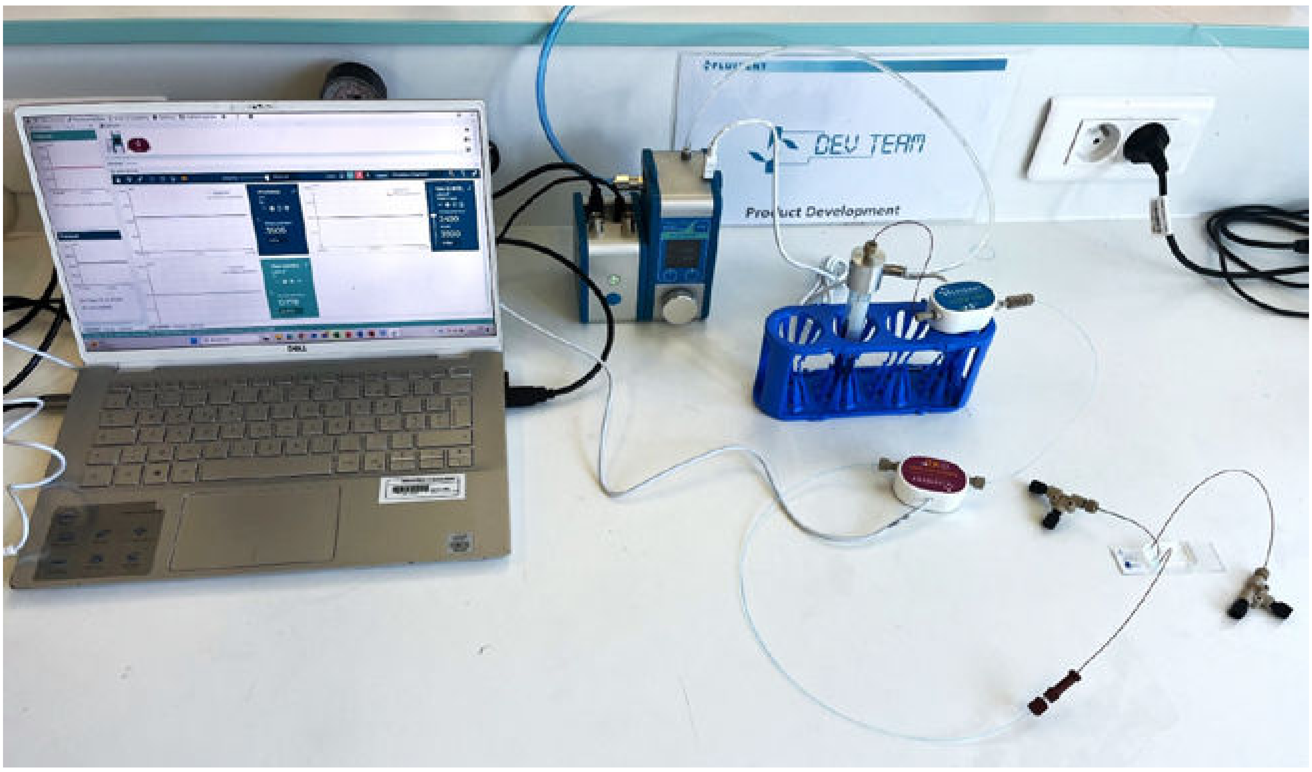
ENSURING QUALITY CONTROL IN MICROFLUIDIC AND OTHER DEVICES BY INNOVATIVE MICRO-LEAK DETECTION METHOD

This application note illustrates how advanced flow and pressure control systems support rigorous, liquid-based micro-leak detection.



INTRODUCTION

Micro-scale devices have applications across multiple fields, including preventive medicine, pharmacology, and environmental sciences.

To ensure the safety and efficacy of microfluidic systems, rigorous quality testing is usually necessary. When developing a microfluidic system, particular attention should be paid to micro-leakages. In fact, they can compromise the performance of these systems. These can arise from various factors, including material quality, mechanical stress, manufacturing defects, or material aging. These issues can lead to a loss of reliability and device functionality, which can ultimately lead to product failures (e.g., loss of valuable samples, poor repeatability).

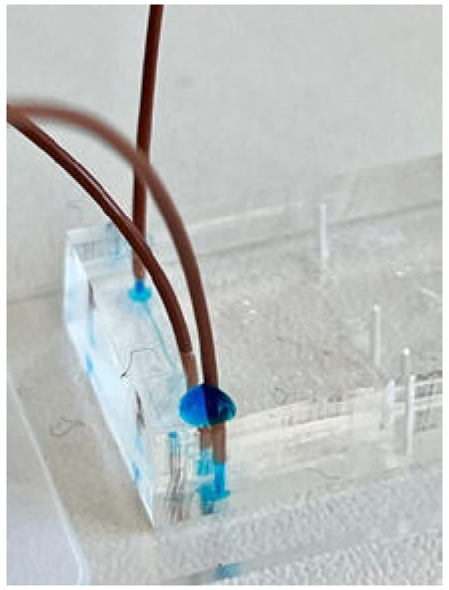


Figure 1: Leakage at a connection point in a PDMS chip

Leakage characterization can be performed during system qualification across divers applications. In microfabrication, for example, verifying the integrity of microchannels at different pressures or flow rates is crucial. In digital PCR, characterizing valve leakage is essential to ensure accuracy [1]. Micro-leak detection is also relevant in lab-on-chip and organ-on-chip systems, where maintaining a sealed environment is required for proper operation [2].

This application note outlines several methods for detecting and characterizing leaks in microfluidic devices, along with the protocol and results of a chip burst test conducted using the Leakage Testing Package, which enables precise nanoleak detection and characterization.

DIFFERENT METHODS FOR MICRO-LEAK DETECTION

In micro-leak detection, both gas-based and liquid-based methods are used across multiple test conditions to evaluate a device's reliability.

MAXIMUM OPERATIONAL PRESSURE TEST

Some tests ensure the device or system meets specifications and can withstand operational pressures without leaking. This type of test can be part of the quality control process in manufacturing for devices. These tests are typically performed at 1.5 times the maximum operational pressure to characterize a product or system before distribution and confirm there are no leaks. [3]

BURST TEST

Additionally, burst tests can be conducted to determine the maximum pressure a device can withstand before leakage occurs. This type of test can be used to characterize a component or product and fill the results in the datasheet. This is a destructive test.

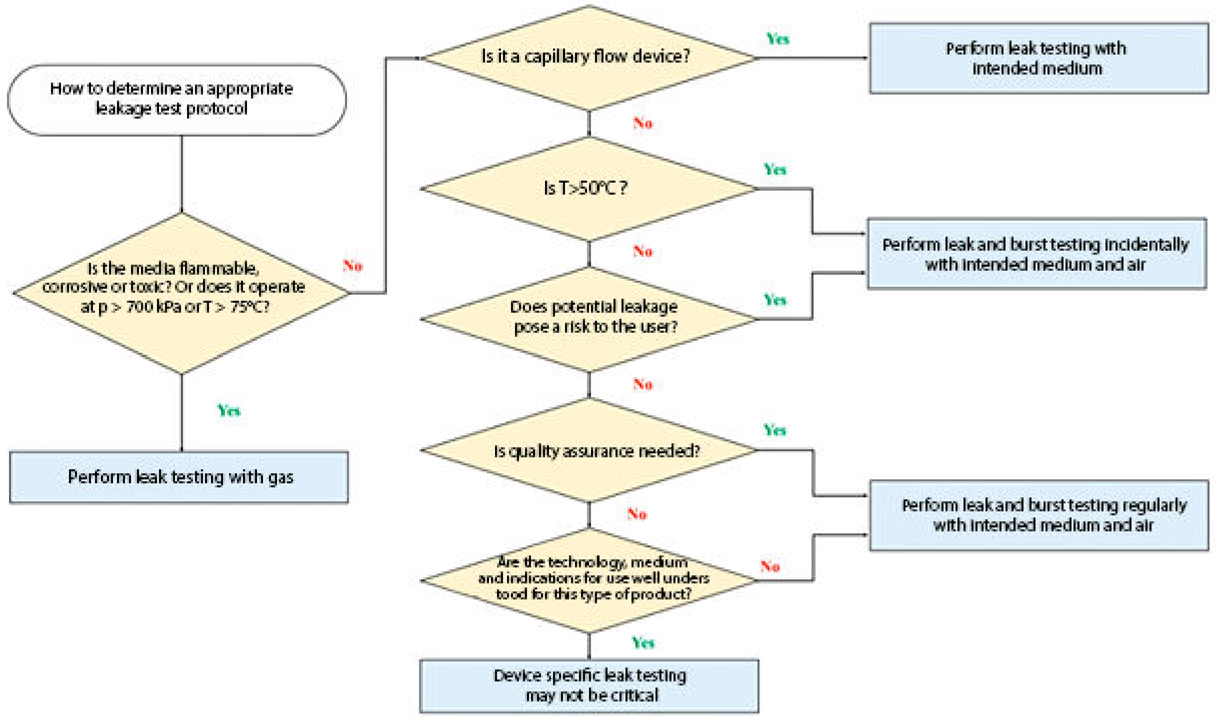


Figure 2: How to choose the right leak test protocol for your product and the conditions of your experiments [3]

Gas-based testing

The principle of gas-based leakage testing is based on directly detecting escaping gas from the device. Its main advantages are the non-contaminating and non-destructive nature of these tests.

This can be used on a closed system by applying a constant pressure, which is monitored by a pneumatic pressure sensor or a pressure transducer. If a pressure drop is observed, it indicates a leak. With precise measurement, gas-based testing is highly sensitive, allowing for the detection of even small leaks (order of tenths mbar).
However, using this micro-leak detection method, locating the exact source of the leakage can be difficult. A challenge is the correlation between the gas leakage rate and the leakage rate of the actual medium, as viscosity differences may lead to varying results [4]. Therefore, it may be more useful as a qualitative approach rather than a quantitative approach.

Finally, some precautions must be taken, such as using dry air or inert gases like nitrogen, to avoid damaging the device during testing and minimizing the internal volume of the test setup to optimize the sensitivity of the manometer [3].

Liquid-based testing

Liquid-based testing methods rely on external pressure sources and manometers to pressurize a sealed system filled with a liquid. A common approach for micro-leak detection is to gradually increase the pressure, and, once the source is disconnected, any pressure decay indicates a leak. These methods traditionally use industrial pressure controllers that are limited in precision, as they do not have a fine enough measurement scale. The process can be time-consuming, requiring computer integration and manual adjustments for both the pressure control and flow rate sensor. This complexity adversely affects the performance, speed and consistency of quality control.

To address these challenges, Fluigent's technology offers a fully automated solution with advanced pressure-based flow controllers and high-sensitivity flow sensors that can detect leaks as small as nano leaks. Furthermore, our user-friendly software streamlines the testing process, enabling quick and accurate quantification of leakage rates. This solution reduces testing time and significantly improves reliability, performance and precision. This technique is valuable for characterizing components during development and for quality control at the end of the industrialization process.

LIQUID-BASED BURST TEST AND LEAK DETECTION METHOD USING PRECISE FLOW CONTROL

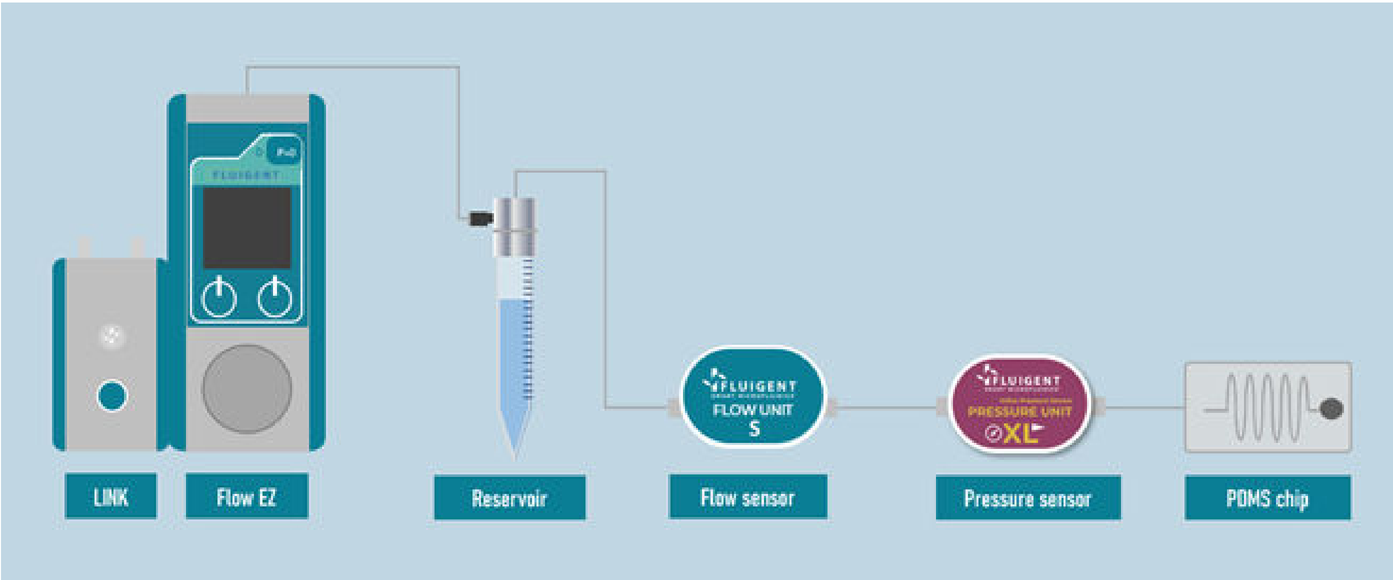
We performed a burst test using a PDMS microfluidic chip. This test allowed to assess the pressure tolerance and burst threshold of the microfluidic channels, which is crucial for ensuring component durability under high-pressure conditions.

MATERIAL & METHODS:

To perform the test, the Flow-EZ pressure controller is used to apply pressure on the system. A flow sensor and a pressure sensor are employed to accurately detect and measure variations in pressure and flow rate upstream of the chip. During the experiment, a flow rate remaining at zero and a stable pressure measurement demonstrates the integrity of the system. If a positive flow or pressure drop is observed, this indicates a leak, which can be quantified precisely through flow rate measurements.

The following equipment was used to perform this experiment:

- Flow EZ 2000 mbar
- Flow UNIT S
- Pressure Unit XL
- LINK
- Homemade PDMS chip
- P-cap
- FLOW UNIT S and M Tubing & Fitting Kit for 1/16" tubing
- P-Cap 50 mL Tubing and Connectors Kit
- Pressure UNIT Tubing & Fitting Kit
- LineUp Supply Kit



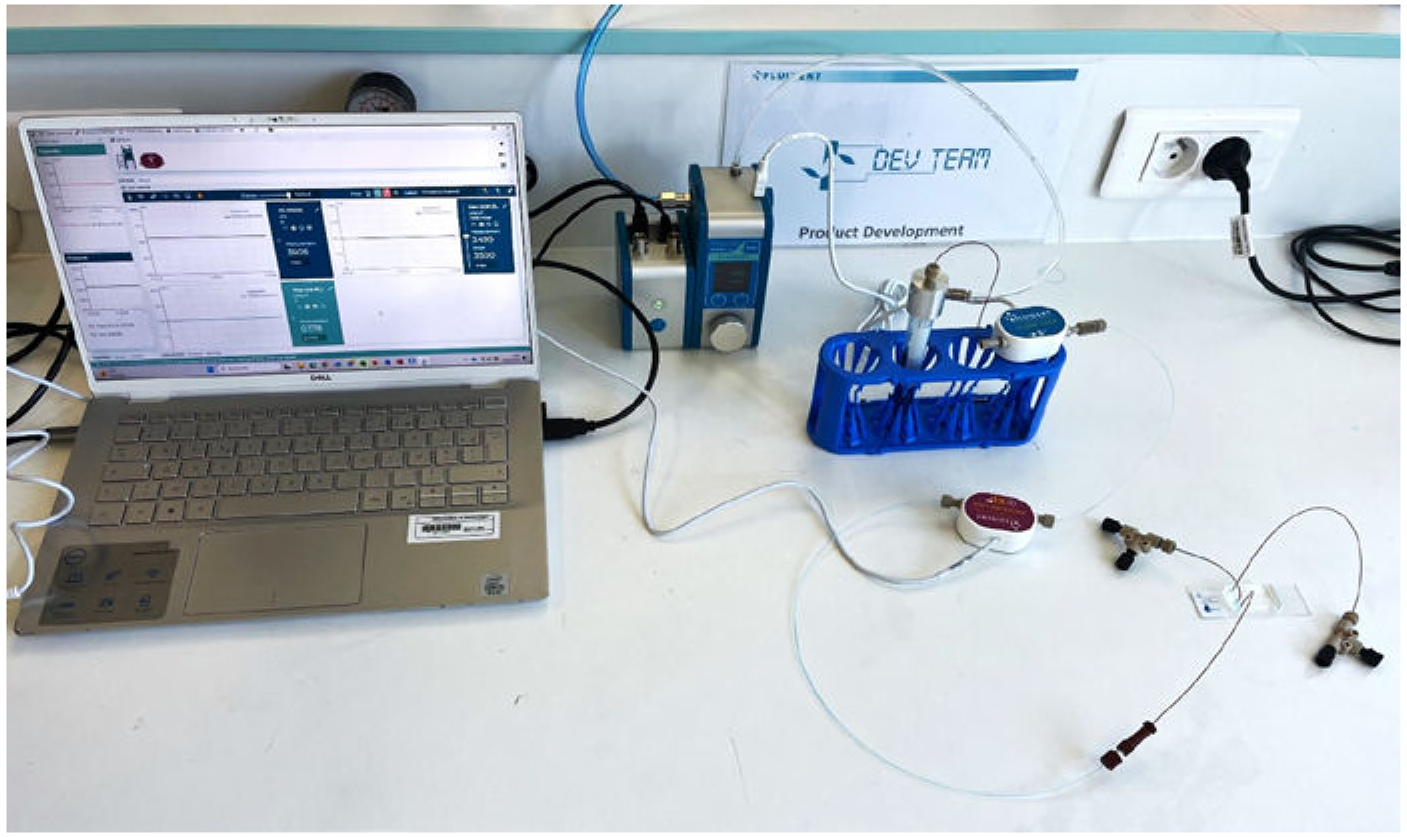


Figure 3: Set-up for leakage testing in a PDMS chip using precise flow control and detection

1. The microfluidic chip is sealed so that the system is closed.
2. The device is filled with DI water (colored water is used here in order to identify the location of the leak).
3. Low pressure is applied, for 30 min so the system can stabilize.
4. Pressure steps from 0 to 3 bar are programmed and maintained for 3 min at each step. This step can be automated using OxyGEN software, which enables the protocol to be created, applied and saved.

RESULTS AND DISCUSSION: NANO- LEAKS DETECTION AND CHIP DELAMINATION

Figure 4 represents the recording of the applied pressure, the pressure measurement and the flow rate measurement over time. Significant spikes in flow rates can be observed at points where pressure was increased. These changes are expected as increasing pressure will temporarily inflate soft tubing, leading to flow rate peaks, rapidly dropping back to a stable flow rate state once the system is back to a steady state.

At an applied pressure of 2900 mbar, we observe a noticeable difference between the controller's pressure measurement and that of the external pressure sensor that is directly connected to the chip. This divergence indicates the presence of an increasing leak in the system. At this pressure level, the leakage flow becomes significant enough to impact the measured pressure, revealing a loss of system containment.

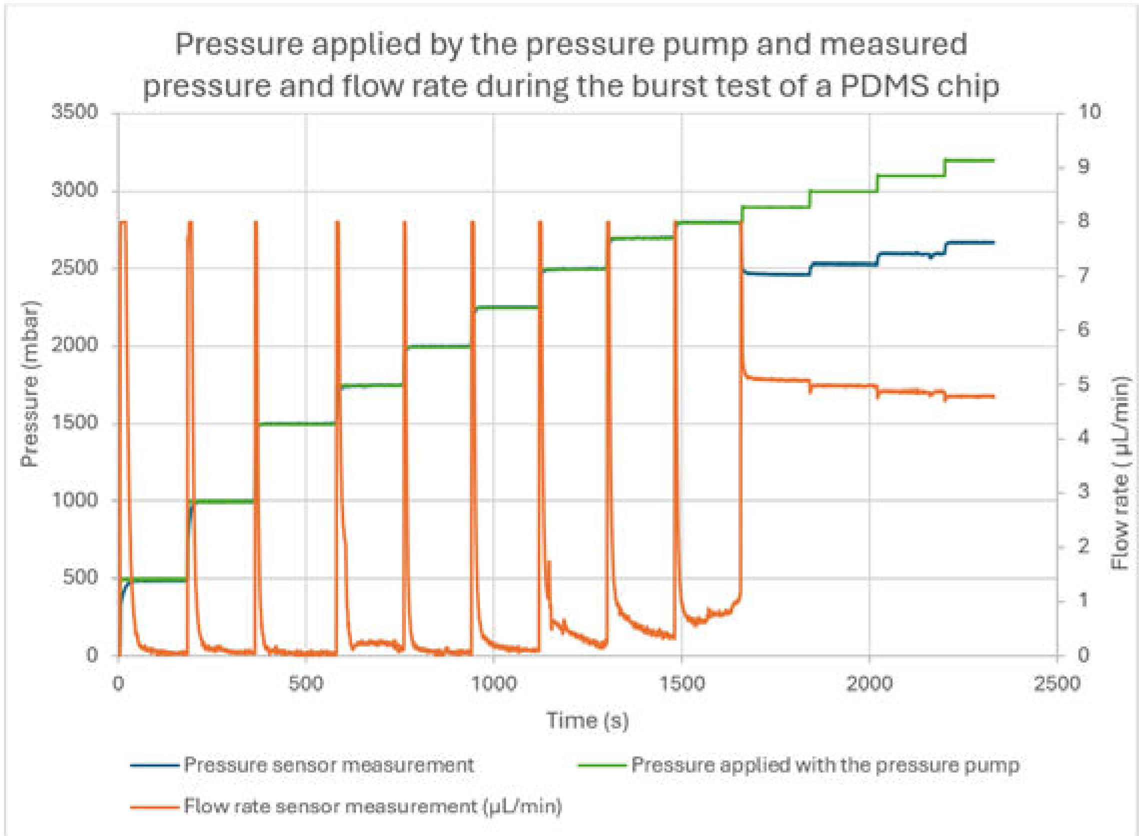
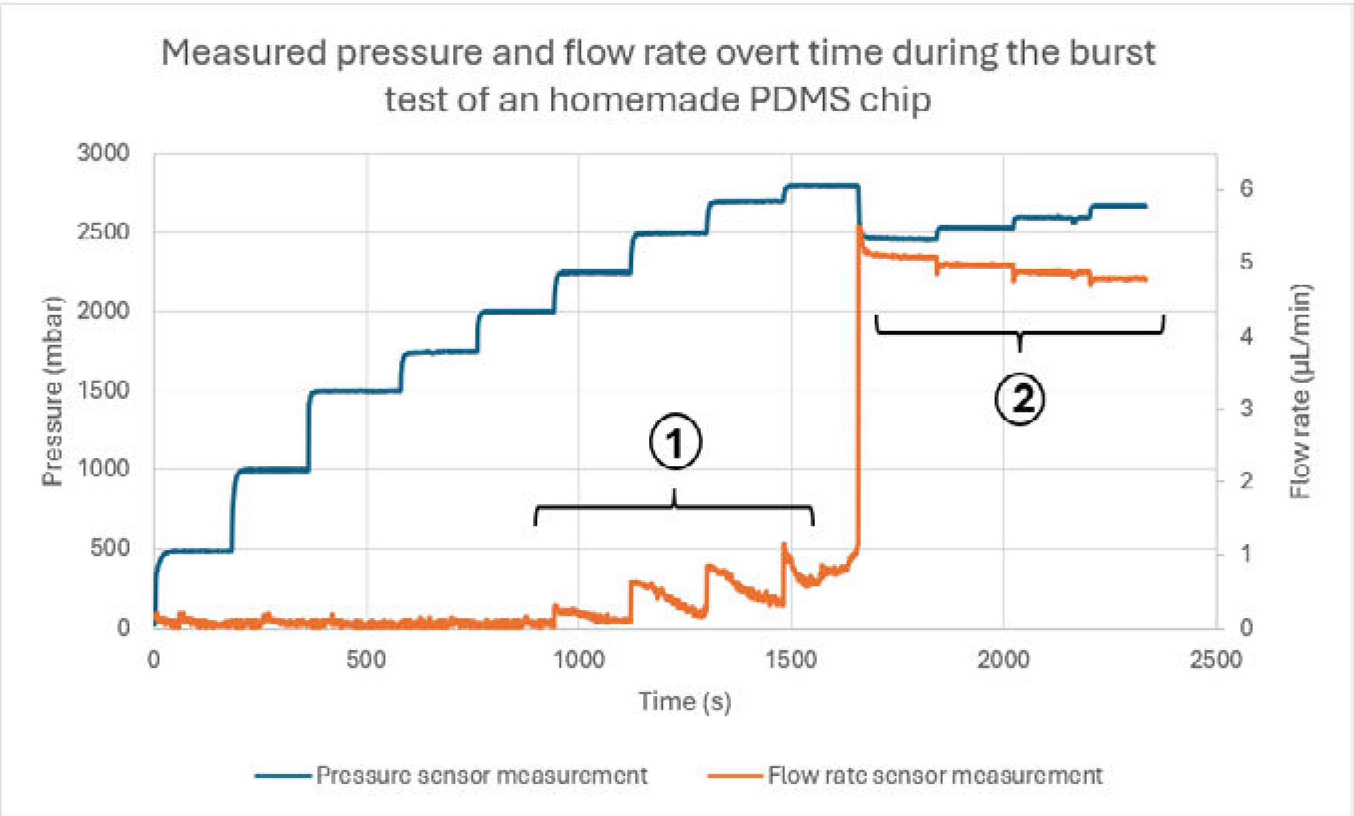
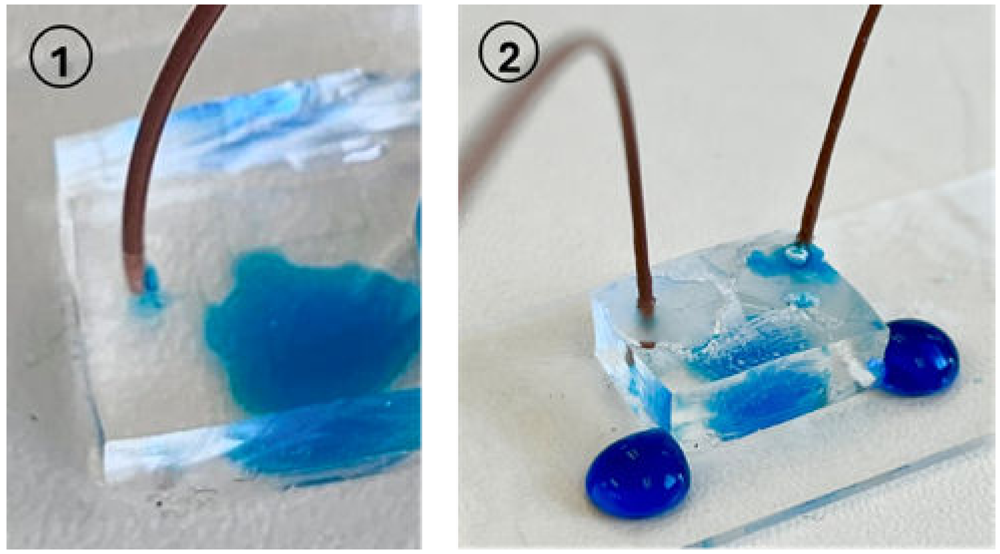


Figure 4: Graph representing the evolution of the applied pressure, the pressure measurement and the flow rate measurement during the burst test of a PDMS chip





1. Leakage resulting from the partial damage of the microfluidic channels.

2. Leakage due to chip delamination.

Figure 5: Graph showing the evolution of pressure and flow rate measurements over time during the chip burst test, with images illustrating the corresponding leakage visualization.

To enhance interpretability, smoothing was applied to the spikes in the graph, resulting in Figure 5. This approach clarifies the overall trends in flow rate by minimizing the impact of transient fluctuations.

Figure 5 illustrates the evolution of pressure and flow rate measurements over time, enabling the detection of leaks in the chip. Above 2250 mbar, a flow rate of hundreds of nL/min is recorded, indicating the first leaks which correspond to partial damage of the microfluidic channels (picture 1). As the applied pressure reaches 3000 mbar, complete delamination of the chip is observed (picture 2), resulting in significantly higher leakage rates of approximately 5 µL/min. This sudden increase in leakage is accompanied by a noticeable drop and instability in the pressure measurements by the sensor.

The test results indicate that the flow rate remains at zero and stable until a leak occurs, confirming the system's integrity under the applied pressure conditions. Moreover, our results highlight the device's precision in early leak detection. With the ability to detect flow rates as low as nL/min, this system can accurately quantify leakage rates, enabling users to assess the severity of leaks. This capability provides critical data for effective characterization and quality validation in microfluidic applications.

CONCLUSION AND OUTLOOK

This application note illustrates how advanced flow and pressure control systems support rigorous, liquid-based micro-leak detection. Results show that the system accurately identifies even the smallest leaks. With flow rates measurements as low as nL/min and pressure drops detection, it allowed an accurate and precise leak rate quantification during chip burst testing.

The test was conducted on a microfluidic chip but can be extended to broader applications in quality control and characterization, such as product development and industrial test bench setup. Fluigent's products are highly precise, stable, and easy to use, providing integrated automation that ensures reliability and seamless integration into industrial quality control processes.

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