Instruments diagnostics by harnessing sensor data

As automation and digitalization continue to drive productivity and efficiency improvements in laboratories, commonly known as Lab 4.0, the importance of data generation, collection and analysis has become indisputable. Data extracted from the wide variety of lab instruments brings key insights to optimize processes and ensure reproducible experiments with a high degree of control.

One of the major characteristics sought by end-users in laboratory instruments is robustness, which denotes a machine's capacity to operate reliably over extended periods with minimal unexpected downtime.

The rationale behind this emphasis is clear: malfunctioning instruments result in wasted labor costs and experiment delays while awaiting repairs, potentially leading to the loss of expensive samples.

Moreover, whether it is chromatography systems, hematology analyzers or flow cytometers, the increasing complexity of such instruments necessitates frequent, prolonged, and costly maintenance operations.

Sensors, as primary sources of data in labs, can help mitigate downtime and reduce maintenance duration through predictive maintenance and instruments diagnostics.

How sensors improve instrument robustness and reliability

Most typologies of analytical instruments require controlling the dosing of reagents, the flow of carrier gases or liquids, or the sample injection. To meet these purposes, such instruments often integrate gas or liquid flow sensors. Sensirion's micro-thermal flow sensors are widely used, as they offer high repeatability, dynamic range, and sensitivity. With flow rate measurement ranges reaching down to nanoliters per minute, the sensor's signal can also deliver significant information about the instruments' health: this is referred to as "more-than-flow" capability.

To illustrate this, we explore various use-cases below, followed by a dive into the sensors' operational mechanisms. Real measurement data from an experimental setup follow as a proof of concept and to provide guidance on how to reproduce the various use cases

Use cases

Valve ringing

As a valve closes to stop the fluid flow through the system while the pump operates at the same speed, ringing occurs. This occurs especially as sealing rings wear out and the valve requires more time to settle into its closed position (**Fig. 1**). The flow sensor, due to its high sensitivity, shows large fluctuations with negative values reflecting backflow that can disturb the instrument's functioning.

Detecting such ringing, which can also result from mechanical vibrations, allows optimization of the setup. Refer to Figure 9 in the next section for experimental results.

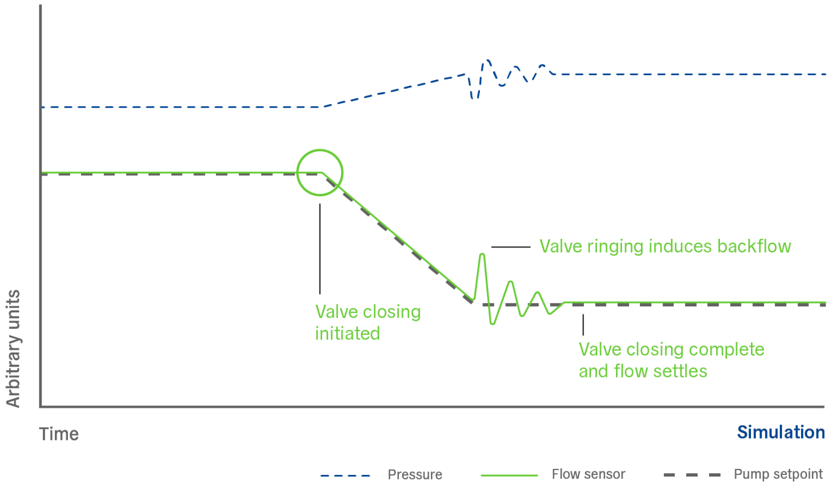

Figure 1 Simulated results of valve ringing with the flow sensor reading shown in green, pressure curve in blue and the pump flow setpoint in black.

Mechanical wear

Another example of more-than-flow sensing is the detection of wear over time (**Fig. 2**). This phenomenon manifests itself on the flow sensor in several ways: a noisy signal, due to pump malfunctions, incorrect flow levels caused by increasing leakages, as well as oscillations reflecting vibrations in the instrument. Refer to Figure 8 in the next section for experimental results.

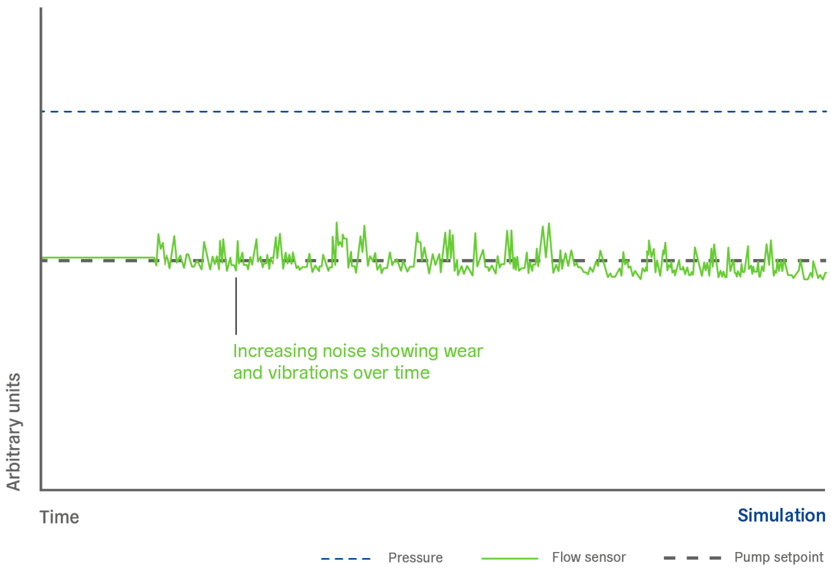

Figure 2 Simulated results of mechanical wear with the flow sensor reading showing large noise levels in green, the pressure curve does not detect the wear (in blue) and the pump flow set-point in black

Bubble detection in liquids

Due to the difference in thermal conductivity between a given liquid and air, bubbles can be detected by Sensirion's liquid flow sensors (**Fig. 3**). Two cases can be identified depending on the bubble size. For large bubbles, the flow would reach a zero value as air flows through the sensor. For smaller bubbles, only spikes are observed as the flow does not have time to reach zero. The spike is explained by the large difference in temperature between the thermopiles as the bubble is passing by. Such data cannot be obtained through pressure sensing given the negligeable effect of bubbles on pressure. Refer to Figure 10 in the next section for experimental results with smaller bubbles.

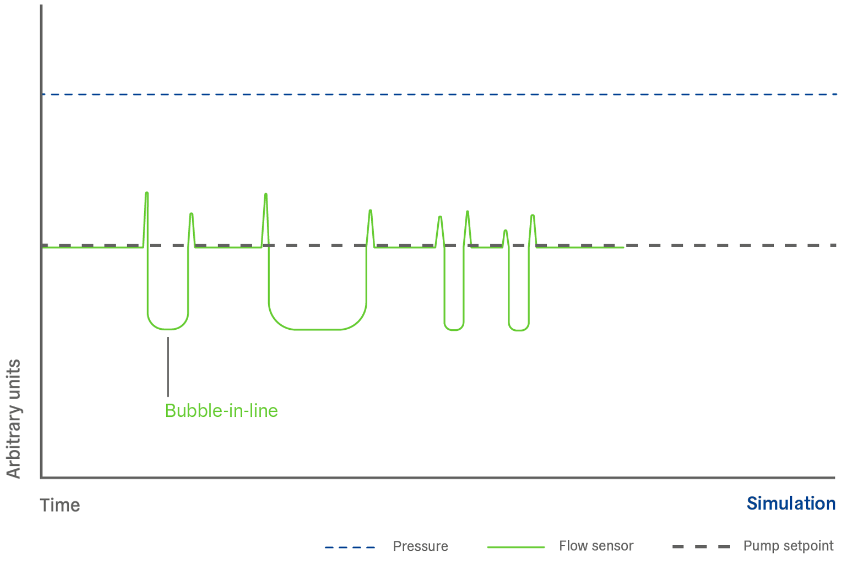

Figure 3 Simulated results of bubbles detected by the flow sensor and not the pressure sensor, due to the thermal conductivity difference between air and liquid. Sensor readout are represented in green, pressure in blue and te pump flow setpoint in black.

Clogging

Obstructions in the flow path alter the flow rate and can eventually lead to a tube burst or instrument damage (Fig. 4). Once an occlusion forms, the flow rate is below its set point and pressure starts building up, eventually saturating. When detected, some occlusions can be cleared by flushing the tubing or mechanically removed; the flow and pressure then recover.

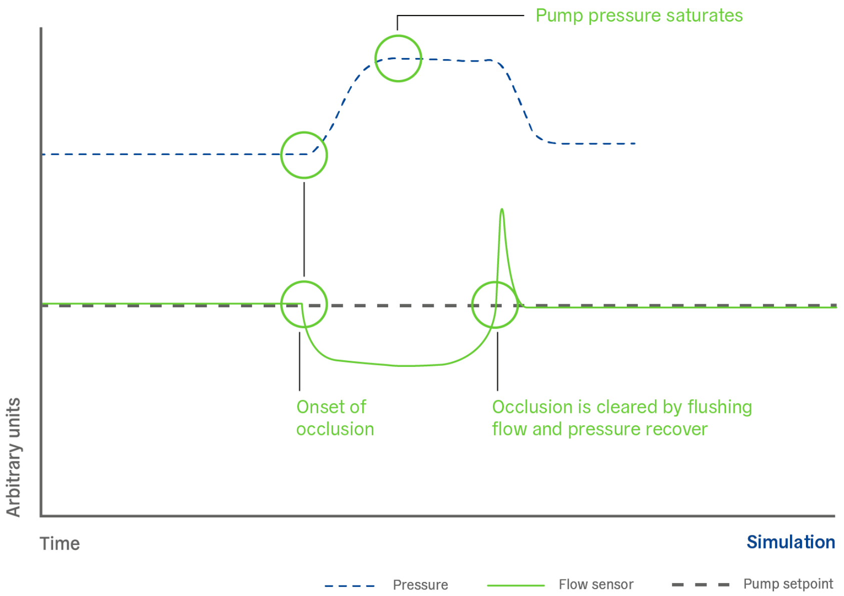

Figure 4 Simulated results of the effect caused by clogging, the sensor reads a lower flow, shown in green, while the pressure sensor shows an increased pressure, in blue. The pump original setpoint is represented in black

Pump flow rate correction

In various cases, a pump may not deliver the expected flow. This can be due to leakage or a malfunction for example. When connecting a flow sensor in a feedback (or PID) loop with the pump, such a behavior can be quickly corrected as the sensor informs the pump that its flow is inaccurate relative to the setpoint (**Fig. 5**). A similar logic can be applied to reduce a pump's noise

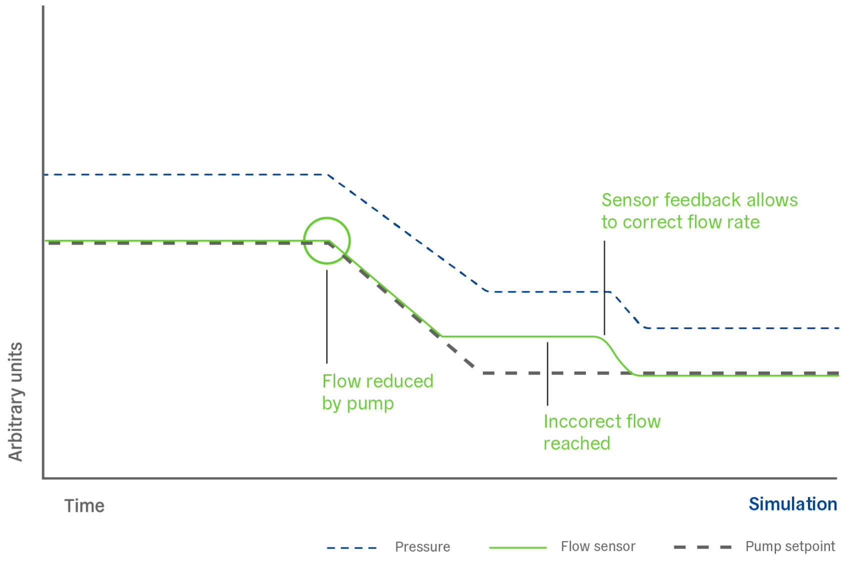

Figure 5 Simulated results of flow correction due to feedback control as the flow sensor detects a higher flow relative to the desired setpoint (green curve). Pressure readout and the pump desi-red flow rate are shown in blue and black, respectively.

Liquid type and temperature detection

Through a measurement at zero flow, the sensor can specify, in arbitrary units, the thermal conductivity of the liquid. This allows to discriminate between various solvents or reagents whose thermal conductivity is known.

Furthermore, a temperature chip on the sensor can be accessed to measure in real-time the liquid's temperature which is a vital parameter in various types of biological measurements.

Operational mechanism of microthermal sensors

Microthermal flow sensing utilizes a heating element on a thin membrane, surrounded by temperature sensors upstream (T1) and downstream of it (T2) (refer to **Fig. 6**).

At zero flow, the temperature difference T2-T1 is equal to 0 due to the symmetric temperature profile generated by the heater.

When a flow is induced, the temperature profile is altered, leading to signal production by the temperature detectors. This mechanism, alongside its high repeatability, facilitates highly sensitive measurements across a broad dynamic range, capable of detecting flow rates as low as nanoliters per minute for liquids and sub-milliliters per minute for gases. This CMOS-compatible design offers cost-effective sensors with a small form factor and easy integration. The chip also contains a temperature sensor to compensate temperature effects and to avoid the need to install additional correction sensors.

Furthermore, a digital process circuit and memory cell are integrated on the chip to process the collected data and to store the calibration curves.

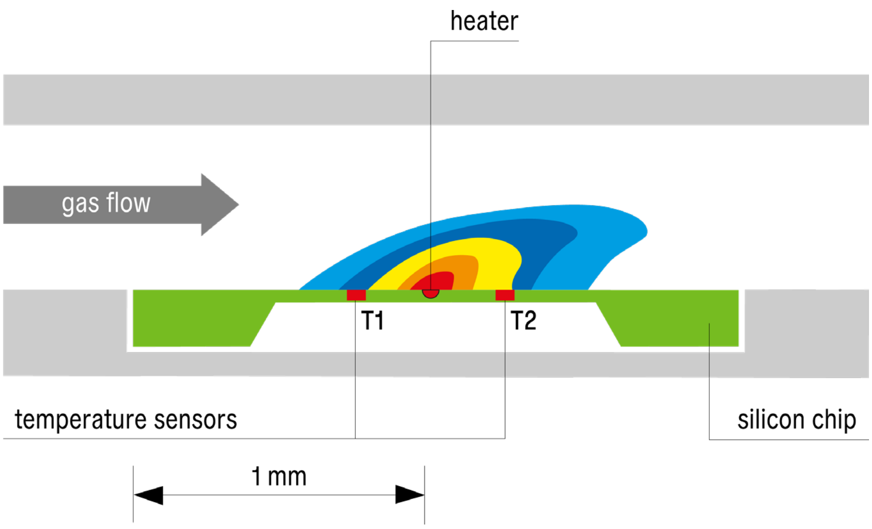

Figure 6 Schematic of the flow sensor cross-section, showing two temperature detectors and a heater in between, crucial to the operation of a microthermal sensor

Implementing an experimental setup

The presented measurements above were performed on a setup consisting of a closed-loop tube system. A water-ethanol mixture was used as test liquid. Liquid flow rates were generated by either a peristaltic pump or enforced by gravity to minimize influences of the pump (**Fig. 7**). The flow signal was measured by using a Sensirion SLF-3S-1300F sensor. Furthermore, the setup was equipped with a solenoid valve and ports for introducing air bubbles into the system. This arrangement represents a generic setup to demonstrate the detection of a liquid flow system's state regarding various aspects.

Note that the actual implementation, sensitivity and performance depends on the individual application.

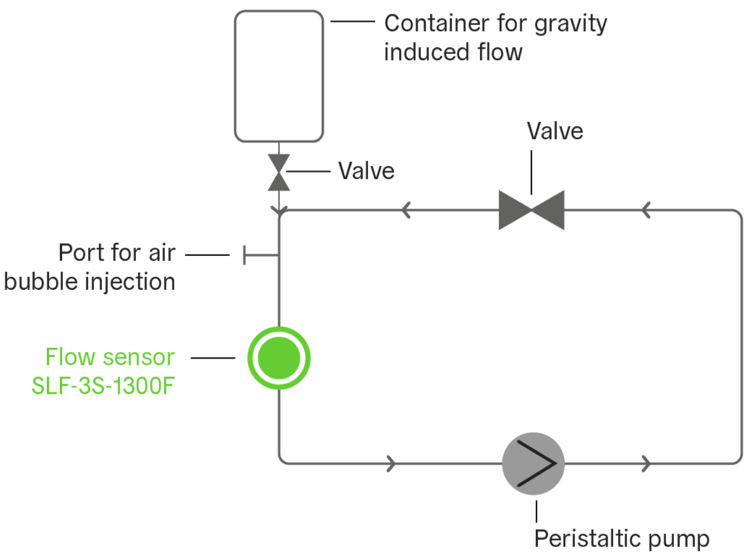

Figure 7 Experimental setup schematic to illustrate various use-cases

Figure 8 shows an initial steady flow rate. As soon as the peristaltic pump is switched on, its characteristic mechanical behavior is reflected in the sensor signal. The sensitivity of Sensirion's liquid flow sensors allows to detect irregularities in pump behavior (e.g., caused by wear and tear) and therefore intervene before a complete failure of the system occurs.

Figure 9 shows the effect of opening and closing a valve on the flow signal. Closing the valve and therefore stopping the flow initiates a typical oscillation of the flow signal leading to backflow (indicated by the green circle).

Sensirion's accurate and reliable liquid flow sensors allow to spot times where back flow occurs. This helps to monitor the overall state of the system and optimize its performance as the valve wears out over time

Figure 10 shows the effects of air bubbles within the liquid flow system on the sensor signal (spikes). This is possible due to the high sensitivity and fast response time of Sensirion's liquid flow sensors. Identifying air bubbles allows to detect potential leaks or outgassing in the system.

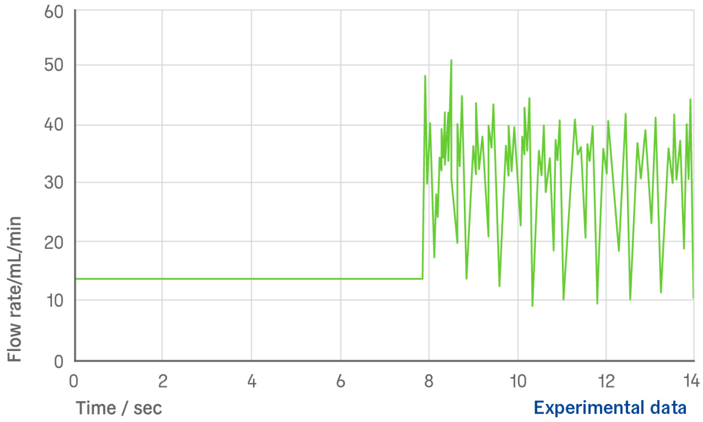

Figure 8 Peristaltic pump mechanical behavior detection through sensor readout (green curve)

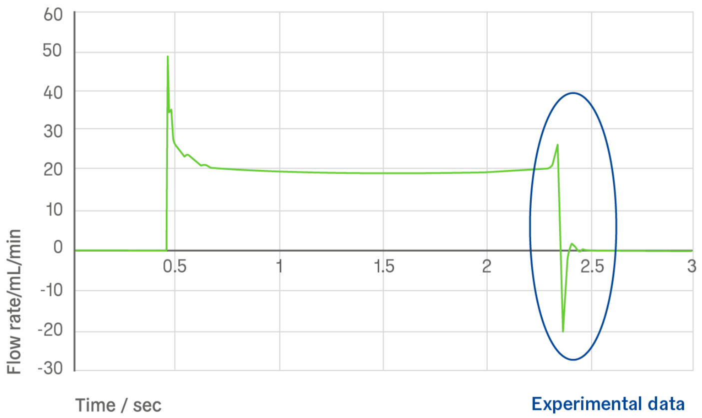

Figure 9 Experimental data representing the opening and closing of a valve which cause overshoots before stabilizing the flow

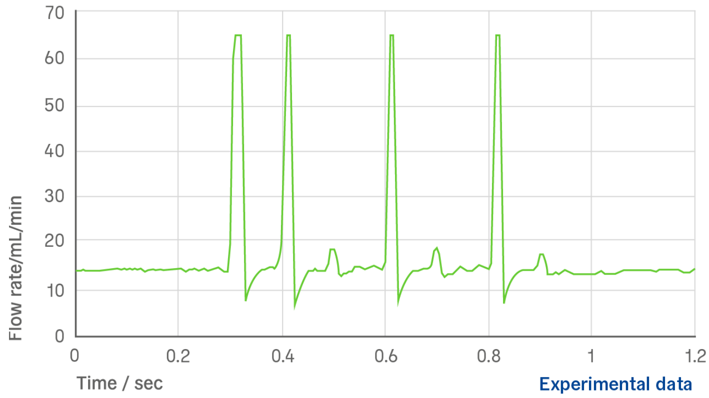

Figure 10 Experimental data illustrating bubble detection as spikes in the sensor signal

A final note for flow versus pressure sensing

- Pressure (or differential pressure) sensors are largely used in life sciences for their affordability and ability to provide information on the system's health (e.g: clogging leads to high pressure).
- In some cases, it is even required to have pressure sensors for safety reasons such as in high-performance liquid chromatography (HPLC) where the column pressure is critical.
- On the other hand, microthermal flow sensors offer superior dynamic range and sensitivity, besides enabling a larger amount of use cases, as shown above. Flow sensors reduce the need for multiple sensors and enable cost reduction while enabling earlier failure prediction.
- In the ideal case, one would combine both sensors to provide a holistic view and more effective instrument diagnostics.

Conclusion

In essence, Lab 4.0 trends have highlighted the vital role of data within labs. Such data can be used to enhance instrument robustness, Flow of Liquid evaporating and turning into data and graphics maximize uptime, and maintain experiment integrity. Sensirion's microthermal technology enhances instrument diagnostics capabilities with high repeatability and sensitivity. Various use-cases demonstrate its effectiveness in detecting anomalies and ensuring instrument's performance.

To start your diagnostics journey, reach out to us for more information and evaluation kits of our various flow sensors.

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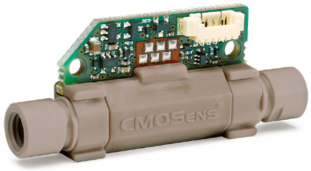

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