



Flow Sensor Solutions in Modern Medical Ventilators

Continuous airflow measurements during anesthesia monitoring, intensive care treatment as well as in clinical and ambulatory environments provide important information for the assessment of cardiorespiratory and breathing circuit behavior and have become indispensable in modern medicine. 90 years after the first use of the iron lung, we are now dealing with mechanical ventilation systems that supply the patient with breathing gas by means of mechanical “air pumps”. This ventilation technique uses positive pressure to deliver air to the patient’s lungs. The increase of intelligent features incorporated into these ventilators, allow them to automatically adapt to changes in lung function or patient breathing. Modern pressure-controlled or volume-controlled ventilation is therefore now more patient oriented than ever. Since fewer and fewer ventilation modes are required due to the increase in device intelligence, medical ventilators have overall become less complex to operate. An interesting example for above points is that while in the past spontaneous respiration in invasively ventilated patients was suppressed by sedation to facilitate mechanical ventilation, nowadays the benefits of spontaneous ventilation are understood and one targets to maintain it over as long a period as possible, often leading to better outcomes.

Ventilation Therapies

Non-invasive ventilation refers to ventilation therapies that are performed using masks or nasal cannulas. This is often referred to as mask ventilation or NIV/NPPV (non-invasive ventilation or non-invasive positive pressure ventilation). In invasive ventilation, an endotracheal tube or a tracheal cannula is inserted into the trachea of the patient to supply the lungs with air. Both types of ventilation – non-invasive and invasive – have merit and are used in a complementary manner. Non-invasive ventilation is often implemented prior to intubation or after extubation in a clinical setting. Another classic application of NIV therapy is the home care setting, where it provides ventilation support to patients without constant oversight by medical professionals. Often a distinction is made between sophisticated ventilators for intensive care, equipped with a non-invasive ventilation option, and less complex non-invasive ventilators for use in subacute care and home care settings.

Use of Humidifiers

A factor that should not be underestimated is the humidification of the inhaled air as it goes far beyond mere patient comfort. Although non-invasive ventilation does not bypass the upper respiratory tract and some humidification of inhaled air still occurs naturally, it is common to use a humidification system, particularly for patients who breathe through their mouths. Well-humidified and warmed air contributes significantly to the success of ventilation therapy as it improves both secretion drainage and the tolerance of non-invasive ventilation therapy [1].

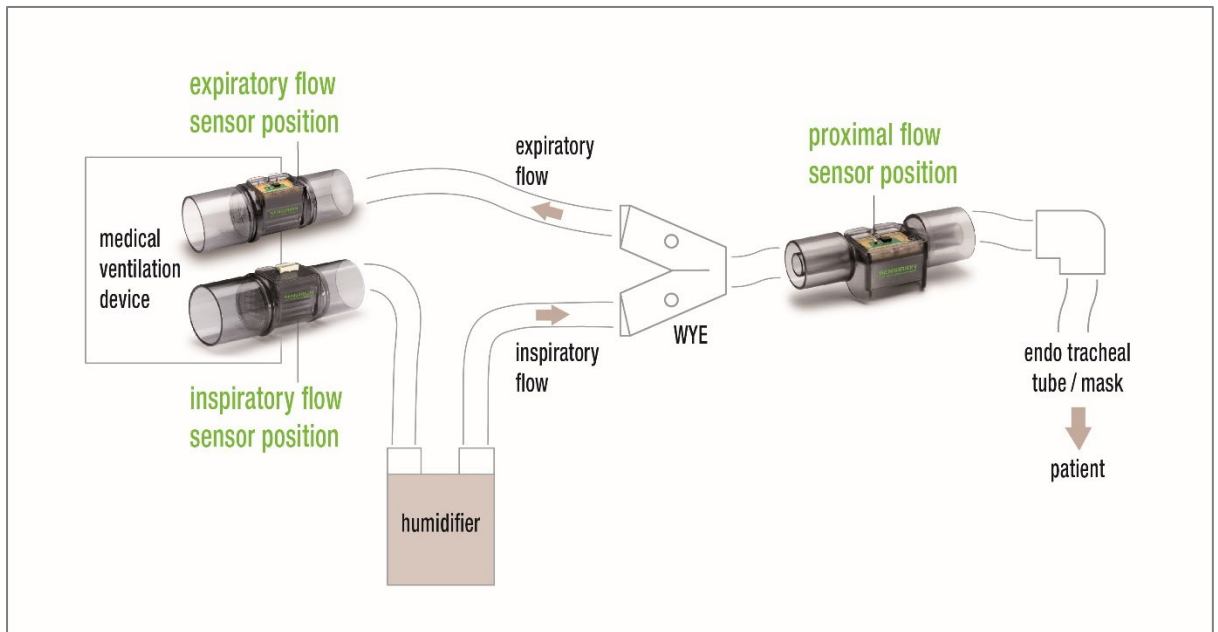


Figure 1: Schematic construction of a ventilator with the typical different sensor positions and the use of a humidifier.

Ventilation Therapy – Trends

Current trends in hospitals show that non-invasive ventilation is used more frequently today and for far more symptoms than ever before. Patients with chronic obstructive pulmonary disease form a large fraction of the patient population treated with non-invasive ventilation in intensive care units. In the case of acute respiratory failure, for example, intensive care units increasingly use non-invasive ventilation as a first-line of treatment, which reduces infectious complications, weaning periods, ICU stay lengths, intubation rates [2] and costs. Also in the home care setting the use of non-invasive long-term ventilation for lung diseases such as COPD, pulmonary fibrosis or cystic fibrosis is increasing.

The key issue for all ventilators is the accurate measurement of the breathing gas flow rate and the volume of breathing gas that flows in and out of the patient. These measurements with the highest sensitivity and accuracy enable the previously mentioned and nowadays prevailing patient-oriented ventilation, which also better reflects the pathophysiology of the patient. For example, the monitoring of pressure, mass flow and volume flow over time allows us to observe changes in the patient's condition, such as reduced lung capacity. Figure 1 shows the schematic construction of a ventilator with the typical air flow/sensor positions.

Technical Challenges

The complex breathing circuits have a wide range of composition variability due to the different types of tubing, humidifiers, filters and adapters used. This often results in leaks and imperfections, which is why the inspiratory flow rate (I) sometimes differs significantly from the flow rate that actually reaches the patient. The same applies to the expiratory flow rate (E). Airflow measurements are also hampered by the constant changes in air temperature, humidity and breathing gas composition as well as the contamination of hoses and expiratory/proximal sensors with sputum, pathogens and blood. Due to technical limitations, measurements of inspiratory (I) and expiratory flow rates (E) were performed inside the ventilator in the past. The rough flow values, which were sometimes significantly different to the actually ventilated values, were then corrected as far as possible using complex and often inaccurate compensation algorithms. To counteract this technical challenge, the respiratory flow is now measured as close as possible to the patient, i.e., proximally.

Advantages in Flow Measurement through Proximal Sensors

Originating from neonatology, it is accepted that the best measurement position for patient airflow, volume and pressure measurements is as close as possible, i.e., proximally (P), to the patient [2]. This allows patients to be ventilated with a tidal volume that is as accurate as possible and the effects of the ventilation circuit composition mentioned above are almost entirely eliminated. Particularly for neonatal and pediatric applications that rely on the

accurate measurement of very small flows proximal flow measurement has become the standard. Additional advantages of proximal flow measurement are the instant detection of respiratory signals, to which the ventilator can respond even faster, as well as the detection of leakages. Particularly for reducing the effect of leakages proximal sensors prove helpful in both volume-controlled and pressure-controlled ventilation and help reduce the causes of monitoring and triggering problems.

Keeping Sensor Technology at the Cutting Edge

The continuous development of ventilators has always been linked to the available sensor technology. From rotameters used in the early days to flow measurements with differential pressure sensors over orifices or hot wire anemometers, sensor measurement technology has evolved considerably to keep pace with the ever increasing requirements of ventilators. A next generation development of the hot wire anemometer is the Sensirion CMOSens® Technology, which is used in all Sensirion mass flow sensors and differential pressure sensors. With the CMOSens® Technology, Sensirion has developed an ever-expanding flow sensor range based on MEMS technology (micro-electro- mechanical system) that now covers all the modern ventilator sensor requirements:

- Inspiratory sensor solution (I) for accurate and instant fan control and inspiratory airflow monitoring
- Expiratory sensor solution (E) for balancing the air exhaled by the patient with inspiratory ventilated air
- Proximal sensor solution (P) to measure inhaled and exhaled air directly at the patient with the highest accuracy

Particularly in the case of proximal measurement, the Sensirion sensor range covers both adult and neonatal ventilation applications with single-use and re-usable sensor solutions. Since both the expiratory and proximal sensors come in contact with humid or potentially contaminated patient air, replacement or cleaning is essential. For this reason, all reusable flow sensor solutions can be cleaned using various methods from washing to autoclaving (135°C, >2 bar pressure and 100% relative humidity).



Figure 2: Proximal sensors (single-use and reusable) for adult ventilation.

Benefits of Next-Generation Flow Measurement Technology

Some of the key differences to its predecessor technology, hot wire anemometers, are that the modern flow sensor solutions deliver a digital, fully calibrated and temperature-compensated output signal. The sensors can thus be directly used with the patient and thus without prior time-consuming or periodically required recalibration. Furthermore, the sensors allow to measure airflow symmetrically in both directions. The robust sensor technology does not require zero-point adjustment, does not drift over time and does not need to be calibrated during the life-time of the sensor. The technology also allows hysteresis-free and position-independent use with an impressive dynamic measurement range and a high measurement sensitivity at all flow ranges. Since the measurement signal is processed directly inside the sensor and the output is digital and temperature compensated flow values, no further costly components such as A/D converters are required. All these benefits enable the medical staff to safely, easily and quickly as well as reliably manage patient ventilation, which provides significant advantages when it comes to challenging emergency ventilation as well as in subacute care and home care settings.

Requirements for the (Proximal) Flow Sensors

Challenges on proximal flow sensors are varied and demanding. The sensors must be reliable and cost effective, long-term stable and, moreover, feature numerous other ventilator-specific features (for example, a low pressure drop, a small dead space volume, bidirectional measurement range and a high level of sensitivity) in order to be suited for modern patient-oriented ventilation. In addition, particularly stringent requirements for hygienic sterilization are in place as the sensors come into contact with air that is potentially contaminated with pathogens.

Use with High Humidity

The Achilles' heel of all current air flow sensors on the market is the use in combination with humidifiers. As previously described, humidifiers are used frequently as their importance goes far beyond the patient's comfort during therapy. The high humidity becomes a problem when it leads to condensation, causing macroscopic water droplets to rain out in in the cooler parts of the ventilator circuit. As a solution to this common but challenging application, all Sensirion proximal and expiratory sensors are equipped with an additional external heating element. Operation of this heating element with a maximum of 0.5 W is sufficient to reliably prevent condensation in the sensor and thus ensure long-term stable and reliable operation.

We demonstrated this in a simulated neonatal ventilator case with extremely humid air and a very small tidal volume of only 5 ml. The schematic illustrated in Figure 3 shows a humidifier typically used in ventilator setups to ensure the breathing air is well humidified. The steel cylinder in the oven is kept at 37°C and simulates the lungs of the infant with the connected pressure sensor used as a reference. The controlled valve is closed during the inspiratory breathing cycle and opened once per second for the expiratory part of the breathing cycle.

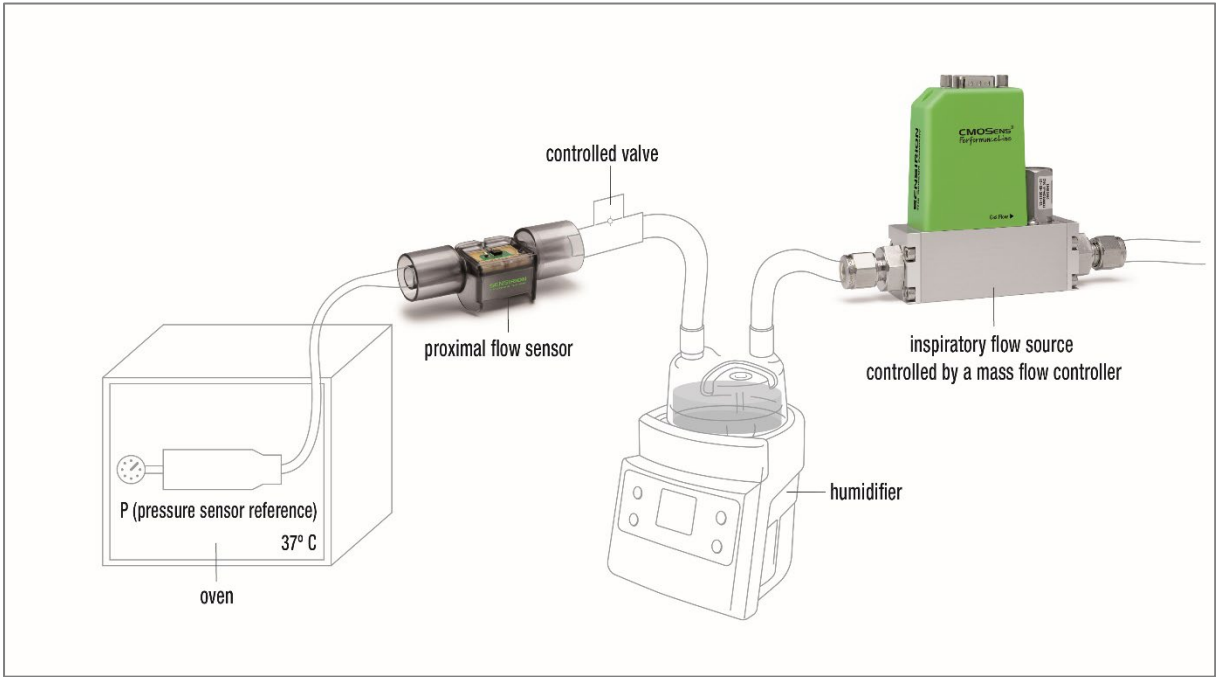


Figure 3. Schematic of a challenging neonatal ventilation setup with extremely humid air and a very small tidal volume of only 5 ml.

Without the use of the heater, you can see how individual drops of water run over the sensor element and cause misreading of the measurement values over the course of 16 hours during the ventilation of the very small 5 ml tidal volume. This misreading can clearly be recognized by the deviations of the expiratory/inspiratory volume from the reference volume shown in Figure 4.

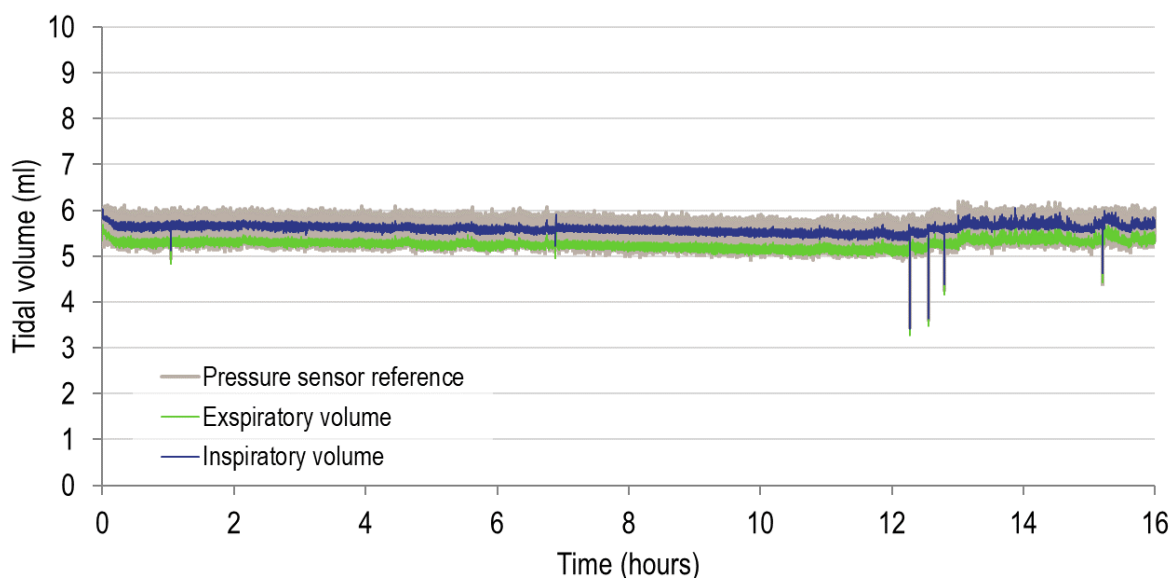
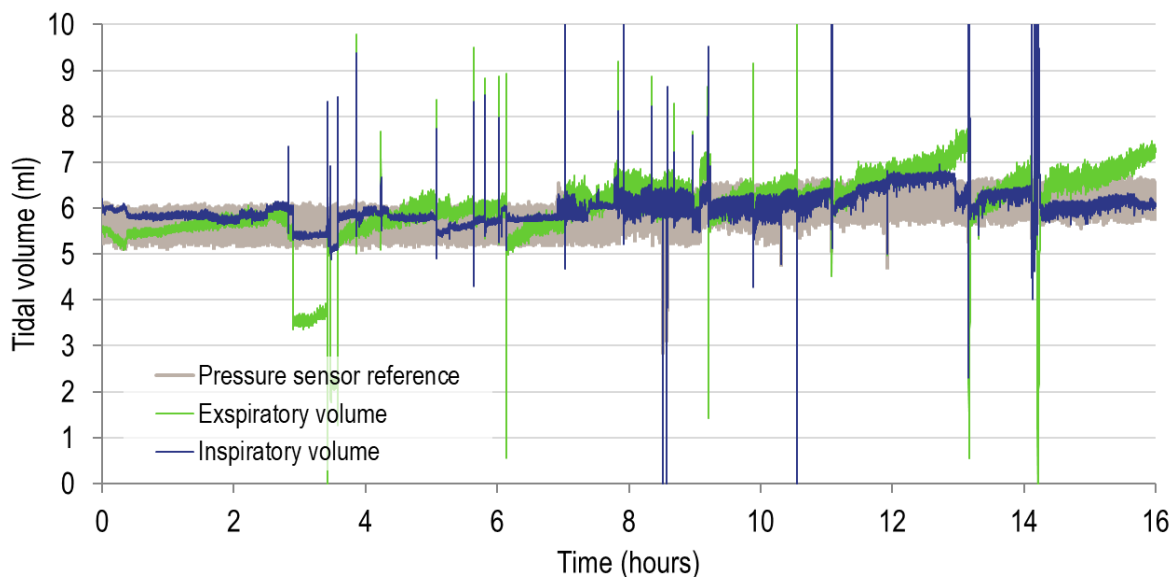


Figure 4. SFM3400 used in very high humidity environment without (above) and with (below) the use of the special external heating element. Inspiratory and expiratory volume is measured with the proximal SFM3400 sensor solution over the duration of 16 hours.

The opposite can be observed when the heating element is switched on. Over the entire course of the 16-hour ventilation period, there was no significant glitch of the proximal measurement reading due to the high humidity condition.

Outlook

The use and spread of ventilators will continue to grow strongly in the future due to the increasing number of lung diseases. Modern ventilators place ever-growing demands on sensors in order to place the focus on the patients and their therapy. The CMOSens® Technology has established a new generation of flow sensors that have proven their reliability millions of times in the field of CPAP devices and automotive applications with the advantages for ventilators being evident. This technological advantage will enable manufacturers to realize the next quantum leaps in ventilation.

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About Sensirion

Based in Staefa, Switzerland, Sensirion AG is one of the world's leading manufacturers of digital micro sensors and systems. The company's product range includes gas and liquid sensors as well as differential pressure and environmental sensors for measuring temperature and humidity, volatile organic compounds (VOC), CO₂ and particulate matter (PM_{2.5}). Offices in the USA, Europe, China, Taiwan, Japan and Korea, allow to support customers with both standard and customized sensor system solutions for a wide range of applications.

Sensirion sensors are widely used in medical, industrial and automotive applications as well as in analytical tools, the consumer goods industry and heating, ventilation, and air conditioning equipment. One of the unique features of Sensirion products is the patented CMOSens® Technology that enables intelligent system integration of the sensor element, logic, calibration data and a digital interface on a single chip. The loyal customer base with many renowned customers and quality management according to ISO/TS16949 certify Sensirion as a reliable sensor company.

Proximal Flow Sensors from Sensirion

Sensirion's proximal sensors for flow measurements in ventilation and anesthesia include sensors for adult ventilation, neonatal and pediatric applications. The proximal flow sensors offer very fast signal processing times, high measurement accuracy and outstanding robustness. The digital and temperature-compensated flow sensors measure bi-directionally and are fully calibrated for air, N₂ and O₂ gases. The special design of the flow channel results in a very low dead space volume. Furthermore, the sensors feature standard medical cones for pneumatic connection to the patient hose system and a mechanical interface that allows a simple and user-friendly electrical connection. The proximal flow sensors are available as single-use and re-usable solutions. The re-usable version is both autoclavable and washable.

Bibliography

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