MEASURING VOLUMES WITH GAS MASS FLOW SENSORS

APPLICATION NOTE FLOW-012 (A4)

There are times with medical instrumentation and in medical device manufacturing when it is necessary to determine the internal volume of a part. The examples provided here illustrate the advantages of using gas with mass flow, pressure and temperature sensors to measure even difficult volumes.

Select the Right Method

In medical instruments and in medical device manufacture it is often important to determine bag volume, control balloon volumes or determine the cavity size in molded parts. Trying to measure these geometries by length measurements can be difficult, if not impossible. It is possible to use a liquid to fill the part to calculate the volume, but this can be messy and time consuming. Another method that is faster and cleaner is to use a gas. Mass flow sensors for gasses are convenient sensors to use in this application.

Measuring Bag Volume

For design or quality assurance purposes, a manufacturer may need to measure the volume of a bag. For a bag that can be totally collapsed, volume can be measured by filling it with gas until the pressure starts to sharply rise, at which point the bag is filled. Starting with the equations:

$$\text{Volume} = \frac{\text{Mass}}{\text{Density}} = \frac{\int_{\text{time}} (\text{Mass flow rate})}{\text{Density}_{\text{final}}} \qquad \text{[Equation 1]}$$

The ideal gas law can be used and the equation can be modified to:

$$\text{Volume} = \frac{\int_{\text{time}} (\text{Standard flow rate}) \times P_{\text{final}}}{\dfrac{P_{\text{standard}} \times T_{\text{absolute standard}}}{T_{\text{absolute final}}}} \qquad \text{[Equation 2]}$$

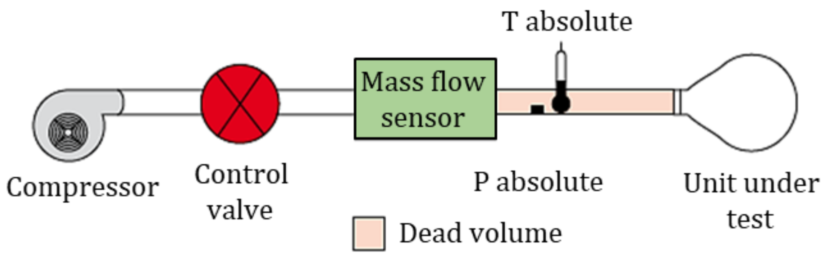
Most thermal-based mass flow sensors give a flow rate that is some type of standard flow rate. Standard flow rate is the volumetric flow rate at a standard temperature and pressure and it is proportional to the mass flow rate for a given gas. Using standard conditions of 760 mmHg and 21.1°C (294.15°K) then:

$$\text{Volume} = \int_{\text{time}} (\text{Standard flow rate}) \times \left(\frac{P_{final}}{760\ \text{mmHg}}\right) \times \left(\frac{294.15°K}{T_{final}}\right) \quad \text{[Equation 3]}$$

It may also be necessary to make a correction for the dead volume between the bag and the flow sensor. For this, the gas added by the partial pressure portion of the dead volume must be subtracted from the total volume delivered (see Equation 4).

$$\text{Volume} = \int_{\text{time}} (\text{Standard flow rate}) \times \left(\frac{P_{final}}{760\ \text{mmHg}}\right) \times \left(\frac{294.15°K}{T_{final}}\right) - \left[\text{Volume}_{Dead} \times \left(\frac{P_{final} - P_{initial}}{P_{final}}\right) \times \left(\frac{T_{initial} - T_{final}}{T_{final}}\right)\right] \quad \text{[Equation 4]}$$

The dead volume correction can be made insignificant by making the dead volume small or having P_{final} and T_{final} near $P_{initial}$ and $T_{initial}$ (see Figure 1).



[Figure 1]

Measuring Balloon Volume

A medical device may need to inflate a balloon to a specific volume. A similar process can also be used to determine when the volume is reached.

In this case, the initial volume of the balloon, if any, must be accounted for and the balloon will increase in size with pressure (see Equation 5).

$$\text{Balloon Volume}_{final} = \int_{\text{time}} (\text{Standard flow rate}) \times \left(\frac{P_{final}}{760\ \text{mmHg}}\right) \times \left(\frac{294.15°K}{T_{final}}\right) - \left[\text{Volume}_{Dead} \times \left(\frac{P_{final} - P_{initial}}{P_{final}}\right) \times \left(\frac{T_{initial} - T_{final}}{T_{final}}\right)\right] + \left[\text{Balloon Volume}_{initial} \times \left(\frac{P_{initial}}{P_{final}}\right) \times \left(\frac{T_{final}}{T_{initial}}\right)\right] \quad \text{[Equation 5]}$$

Unlike example one, in this case it may not be possible to keep the final pressure close to the initial pressure. Thus, unless the dead volume and the balloon's initial volume are not insignificant in comparison to the final balloon volume, these factors (dead volume and initial volume) must be determined.

The next three sections look at some of the issues that arise when measuring the mass flow, pressure and temperature and how to resolve them.

Mass-Flow Measurement

The two major specifications when selecting a mass-flow sensor are total uncertainty and the response time of the measurement. If the flow rate will vary, it is important to use a sensor with good accuracy over that range. It is best to select a mass-flow sensor that gives a percent of reading rather than a percent of full scale sensor. To illustrate this point: suppose there are two meters with 20 L/min full scale range, and one has an uncertainty of 2% of full scale and the other has an uncertainty of 2% of reading. If most of the flow that is being measured during a test is at 2 L/min, then the uncertainty of the measurement made with the 2% of full-scale meter is 2% of 20 L/min, or 0.4 L/min. A more accurate measurement can be made with the 2% of reading meter where the uncertainty of the measurement is 2% of 2L/min, or 0.04 L/min.

The response time of the flow sensor needs to be orders of magnitude less than the measurement time to accurately integrate flow rate. If not, the volume delivered at the beginning of the filling will be under measured. This may or may not be cancelled out by the overstating of the volume at the end of the filling. Many thermal-based mass flow sensors have a response time of seconds, which can mean a long measurement time. Thermal-film-based mass flow sensors will have a response time of milliseconds, which will allow flow delivery times of one second without the sensor response time affecting the results.

Pressure Measurement

Measuring the final pressure is usually an easy task. Things to look for in an absolute pressure transducer are adequate accuracy and response time. If the sensor does not have a response time that is a few orders of magnitude less than the test time, then inflation will have to stop at the end of the test to allow the sensor enough time to output a good final pressure.

Temperature Measurement

Temperature measurement can become a large source of errors if the system is not designed carefully. When gas temperature is changing or different from the temperature of the unit under test or ambient temperature, the gas temperature will probably not be homogeneous. This means that the temperature at the temperature sensor may not be measuring the average gas temperature.

If a compressor is employed to deliver the test gas, the gas may become heated by the compressor. If using bottled gas, the expansion from high pressure to low pressure may create cold gas. In both cases, a heat exchanger could be used to bring the gas to room temperature.

Once the system is designed so that the temperature is not changing significantly, the response time of the temperature sensor becomes unimportant. In selecting the accuracy of the temperature sensor, it is important to note that because the equations use absolute temperature, a temperature sensor with a 1°K (or °C) uncertainty will add less than 0.33% uncertainty to the measurement.

Summary

With some design care, a mass flow sensor, pressure transducer and a temperature sensor can provide a fast and accurate method of measuring many difficult volumes.

References

Kloeppner, R., TSI Incorporated, “Measuring Volumes with Gas Mass Flow Sensors,“ *Medical Device Technology*, September 2005.

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