Pressure Effects on Static Gases

Pressure and the Ideal Gas Law

Pressure is a measure of the force exerted upon a surface. By the Ideal Gas Law (at right), if the gas pressure (P) increases by a factor of 2, the volume of the gas (V) decreases by a factor of 2, all other factors being constant. This occurs because gases are compressible, and their molecules get closer to each other as pressure increases. If the pressure decreases by half, volume doubles. The molar mass (n, the number of particles in the volume) stays the same, regardless of changes in static pressure.

$$PV=nRT$$

Double the pressure:
$$\frac{V}{2}=\frac{nRT}{2P}$$

Halve the pressure:
$$2V=\frac{nRT}{\frac{1}{2}P}$$

P: pressure (static)
V: volume
n: molar mass
R: gas constant
T: temperature

Effects of Pressure on Mass and Volume

Let's picture a flexible container filled with 500 cm^3 of air at atmospheric pressure (1 atm, about 14.696 psia) and standard ambient temperature (25°C).

If we double the pressure to 2 atm, the air molecules get closer together, and the volume is compressed to 250 cm^3. However, the number of air molecules (molar mass) remains the same.

If we halve the original pressure to 0.5 atm, the volume expands to 1000 cm^3. If we halve the pressure again to 0.25 atm, the volume grows to 2000 cm^3.

In each instance, we have neither removed nor added any air, and so the molar mass of air inside the container does not change from its original 500 scm^3 of air.
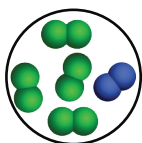
Decreasing pressure increases gas volume.

Air at 1 atm
Mass: 500 scm^3
Volume: 500 cm^3
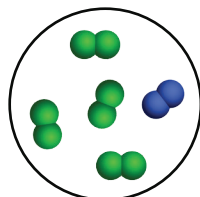
Air at 2 atm
Mass: 500 scm^3
Volume: 250 cm^3

Air at 0.5 atm
Mass: 500 scm^3
Volume: 1000 cm^3
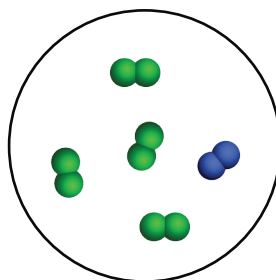
Air at 0.25 atm
Mass: 500 scm^3
Volume: 2000 cm^3
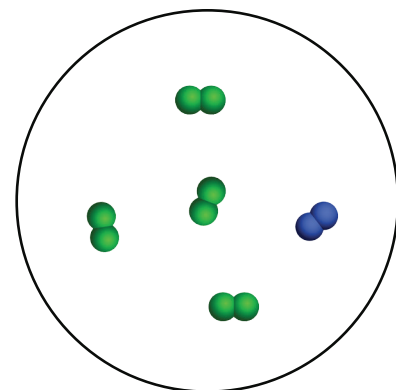
FLUID MECHANICS
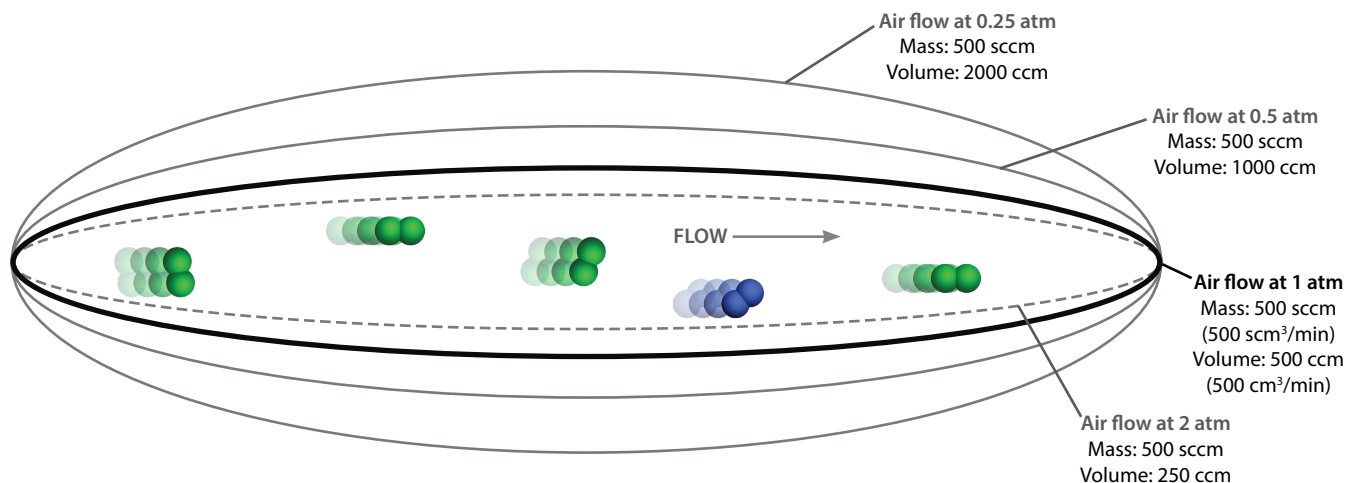
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Pressure Effects on Gases in Motion

Effects of Line Pressure on Mass and Volumetric Flow Rates

When air is put into motion as a flow of gas, the actual space that the air takes up per unit of time (volumetric flow rate) varies with pressure in the same manner as the static air. Doubling the line pressure halves the volumetric flow rate, and vice versa. However, the number of molecules of air that flow per unit of time (mass flow rate) does not change.

Decreasing line pressure increases volumetric flow rate.

Air flow at 0.25 atm
Mass: 500 sccm
Volume: 2000 ccm

Air flow at 0.5 atm
Mass: 500 sccm
Volume: 1000 ccm

FLOW

Air flow at 1 atm
Mass: 500 sccm
(500 scm^3/min)
Volume: 500 ccm
(500 cm^3/min)

Air flow at 2 atm
Mass: 500 sccm
Volume: 250 ccm

Sizing Flow Meters for Subatmospheric Pressures

Differential pressure-based flow meters have internal flow channels that are sized to accommodate the maximum expected volumetric flow rates passing through them. When these meters are used in vacuum applications, they may need to be oversized in order to handle the increased volumetric flow rates at subatmospheric pressures.
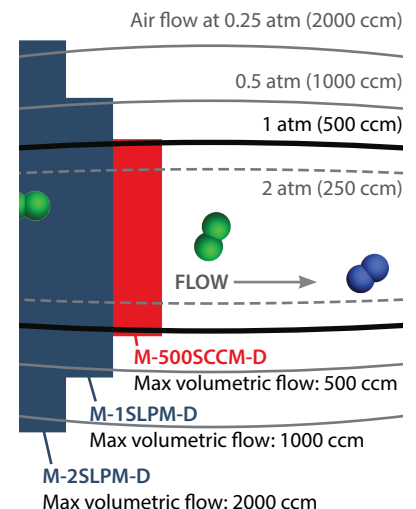
Take for example an Alicat mass flow meter built for 500 sccm (scm^3) at full scale (M-500SCCM-D). If we double the pressure to 2 atm and keep the mass flow rate constant at 500 sccm, the volumetric flow rate decreases to 250 ccm. This decrease in the volume of air flow poses no challenges to flow measurement because the meter is designed to handle twice that amount.

Now, if we reduce the line pressure to 0.5 atm and keep the mass flow rate constant at 500 sccm, the volumetric flow rate doubles to 1000 ccm. The

meter's built-in overrange of 28% allows it to read volumetric flows as high as 640 ccm (which it would see at 0.78 atm), but 1000 ccm at 0.5 atm is too much and produces a 'VOV' error.

Because the flow meters are physically sized for volumetric flows, the solution is to order an oversized flow meter at twice the full-scale range (M-1SLPM-D). The ranges would be specified for the original mass flow range of 500 sccm and a doubled volumetric flow range of 1000 ccm. Similarly, at 0.25 atm the meter would be built for quadruple the flow (M-2SLPM-D) and ranged for 500 sccm and 2000 ccm.

(Note that the maximum oversize is 5x, which would nominally accommodate a line pressure of 0.2 atm, or 2.9 psia. Mass flow ranges normally are not oversized in this scenario, in order to maintain measurement resolution and accuracy over the intended range.)

Air flow at 0.25 atm (2000 ccm)
0.5 atm (1000 ccm)
1 atm (500 ccm)
2 atm (250 ccm)
FLOW

M-500SCCM-D
Max volumetric flow: 500 ccm
M-1SLPM-D
Max volumetric flow: 1000 ccm
M-2SLPM-D
Max volumetric flow: 2000 ccm

Oversize flow meters for use at subatmospheric pressures.

Pressure Drop under Low Pressures

Effects of Line Pressure on Instrument Pressure Drop

Pressure drop is the loss of line pressure caused by frictional resistance in the flow path. This is induced by instruments on the line and even the tube walls to a small degree. Pressure drop tells you how much additional differential pressure must be supplied to attain the desired flow rate.

Pressure drop increases proportionally to volumetric flow rate (flow velocity). Volumetric flow increases as pressure decreases. Thus, pressure drop also increases as line pressure decreases.

At subatmospheric pressures, pressure drops throughout the entire process will be higher than at atmospheric pressures. Ignoring this can hinder the intended operation of the process.

In the chart below, reducing the pressure from 1 atm to 0.25 atm quadruples the volumetric flow rate to 2000 ccm, which quadruples the pressure drop through the 500-ccm flow meter (red). This then requires 4 times the pressure differential (4 psi) to achieve a full-scale flow of 500 sccm.

$$\Delta P \propto Q\eta$$

ΔP: pressure drop
Q: volumetric flow
η: viscosity

A decrease in line pressure increases pressure drop.

Pressure Drop and Oversized Flow Meters

We increase flow channel size to accommodate the higher volumetric flows at subatmospheric pressures. Doing this also provides the benefit of reduced pressure drop.

For example, the flow meters M-500SCCM-D, M-1SLPM-D and M-2SLPM-D each have pressure drops of 1 psi at their full-scale volumetric flow rates. Flowing 500 ccm in the 1000-ccm meter (50% full scale at 1 atm) halves the pressure drop to 0.5 psi. Likewise, flowing 500 ccm in the 2000-ccm meter (25% full scale at 1 atm) yields 0.25 psi of pressure drop.
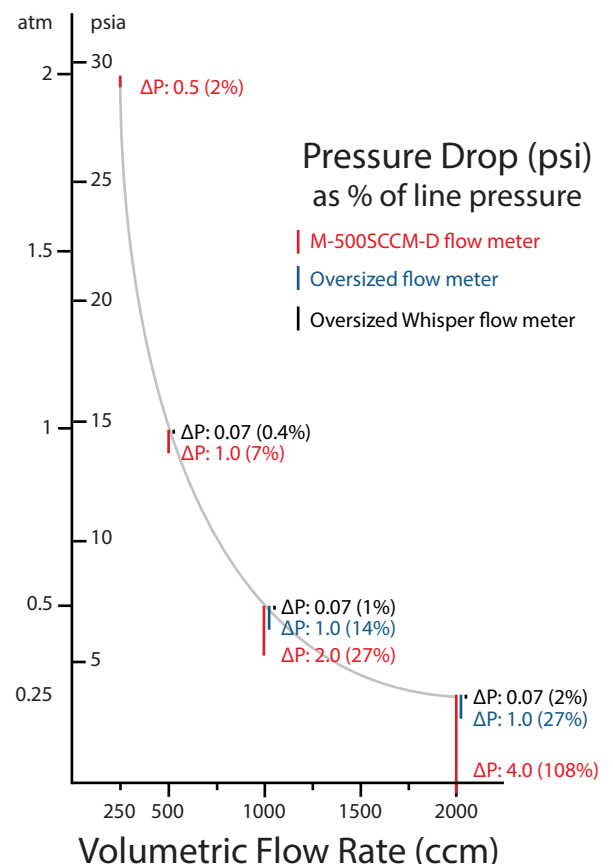
When 500 sccm of mass flow becomes 1000 ccm of volumetric flow at 0.5 atm, using the larger 1000-ccm meter results in the full-scale drop of 1 psi. This is double the drop of 0.5 psi at 500 sccm and 1 atm, because the volumetric flow rate has doubled. Similarly, flowing 500 sccm at 0.25 atm in the 2000-ccm meter also becomes a full-scale flow with a pressure drop of 1 psi.

Use low pressure drop meters for subatmospheric apps.

Low Pressure Drop Meters

Using larger meters to handle subatmospheric volumetric flows also helps to reduce pressure drop, but sometimes this is not enough. In the 0.25 atm example, the lower drop of 1 psi nevertheless represents 27% of the available pressure (3.7 psia), which may be too much to lose. In these cases, it is best to choose a meter with lower pressure drop. An Alicat "Whisper" series meter, sized for 2000 ccm (MW-2000SCCM-D) yields a full-scale pressure drop of only 0.07 psi at 0.25 atm, which is only 2% of the available pressure.

Line Pressure

atm   psia

2 — 30 ΔP: 0.5 (2%)

— 25

Pressure Drop (psi)
as % of line pressure

| M-500SCCM-D flow meter

| Oversized flow meter

| Oversized Whisper flow meter

1.5 —

— 20

1 — 15 ΔP: 0.07 (0.4%)
              ΔP: 1.0 (7%)

— 10

0.5 — ΔP: 0.07 (1%)
              ΔP: 1.0 (14%)
              ΔP: 2.0 (27%)

— 5

0.25 ΔP: 0.07 (2%)
              ΔP: 1.0 (27%)

              ΔP: 4.0 (108%)

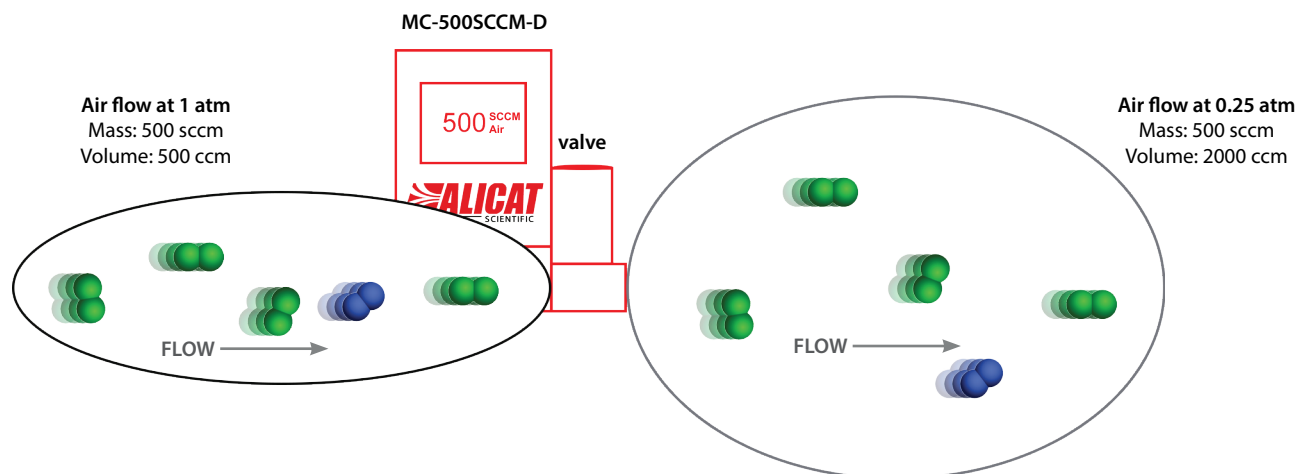250 500   1000   1500   2000

Volumetric Flow Rate (ccm)

Pressure Effects and Flow Controllers

Sizing Flow Controllers for Vacuum and Subatmospheric Conditions

Unlike meters, differential pressure-based mass flow controllers do not need to be oversized for use in subatmospheric conditions. For these applications, the proportional control valve is located at the downstream side of the controller, forming a sonic barrier that shields the sensor from the volumetric expansion of the gas under vacuum. In the example below, the measurement head inside the flow controller always sees flow rates at ambient air pressure (1 atm). Only after the gas passes through the valve does it expand to four times its volume under 0.25 atm of pressure. As in the previous examples, the mass flow rate remains constant as the gas transitions from ambient pressure to subatmospheric pressure.

Request downstream valves on controllers for vacuum apps.

MC-500SCCM-D

Air flow at 1 atm
Mass: 500 sccm
Volume: 500 ccm

500 SCCM Air

valve

FLOW

Air flow at 0.25 atm
Mass: 500 sccm
Volume: 2000 ccm

FLOW

Key Concepts

• Decreasing pressure increases gas volume.

• Decreasing line pressure increases volumetric flow rate.

• Oversize flow meters for use at subatmospheric pressures.

• A decrease in line pressure increases pressure drop.

• Use low pressure drop meters for subatmospheric apps.

• Request downstream valves on controllers for vacuum apps.

Learn more!

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+0.0 SCCM Air
+0.0 +0.0
CCM SCCM TOTAL

A "Whisper" series meter is a great choice for monitoring flows at subatmospheric pressures.

FLOW