First Sensor

LDE/LME/LMI pressure sensors in bypass configuration for gas flowmeters

1. Introduction

1.1 Mass flow $\dot{M}$ and volumetric flow Q

A restrictive element in the main channel defines the relationship between gas flow F and differential pressure (ΔP):

$$F = f(\Delta P)$$

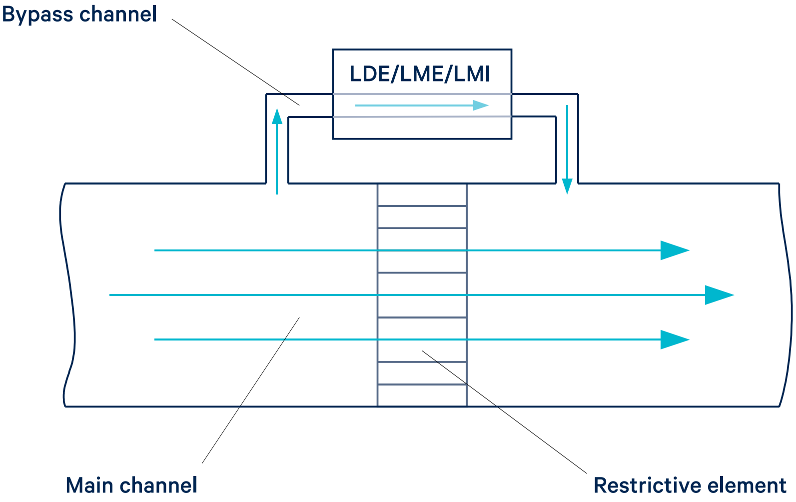

Figure 1: Bypass configuration

Typically, the gas flow F is measured as mass flow $\dot{M}$ [mass per time]. If needed, volumetric flow Q [volume per time] can be derived from mass flow.

The volumetric flow is equal to the mass flow over gas density:

$$Q = \dot{M} / \rho;$$

From the Ideal Gas Law, the gas density can be found as:

$$\rho = (MP) / (RT).$$

Definitions:

ΔP:	pressure drop on a flow-restrictive element;
$\dot{M}$:	mass flow;
Q:	volumetric flow;
ρ:	gas density;
M:	molar mass;
P:	pressure;
R:	gas constant;
T:	absolute temperature.

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1.2 Standard volumetric flow Qs

Standard volumetric flow is a volumetric flow defined at “standard” temperature (T_{std}) and “standard” pressure (P_{std}). Different manufacturers refer to different standards (e.g., T_{std} = 21.1 °C or 70 °F, P_{std} = 101.3 kPa or 14.7 psia).

Commonly used units for standard volumetric flow are “standard liters per minute [slm]” or “standard cubic centimetres per minute [SCCM]”.

For a given gas, volumetric flow at non-standard temperature (T) and non-standard pressure (P) can be found as:

$$Q = Qs\ (Ps/P)\ (T/Ts)$$

1.3 Laminar and orifice-like flow restrictive elements

Ideally, a pressure drop on a laminar restrictive element increases linearly with the flow, while a pressure drop on an orifice increases quadraticly (Figure 2).

While the production cost of a laminar restrictive element is higher, it has two advantages in comparison to an orifice-like restrictor:
- wider flow measurement range ($\Delta F2 > \Delta F1$);
- increased sensitivity around zero flow.

In reality, a flow restrictive element is a combination of the two restrictors described above; either the linear or quadratic pressure-from-flow characteristic dominates.

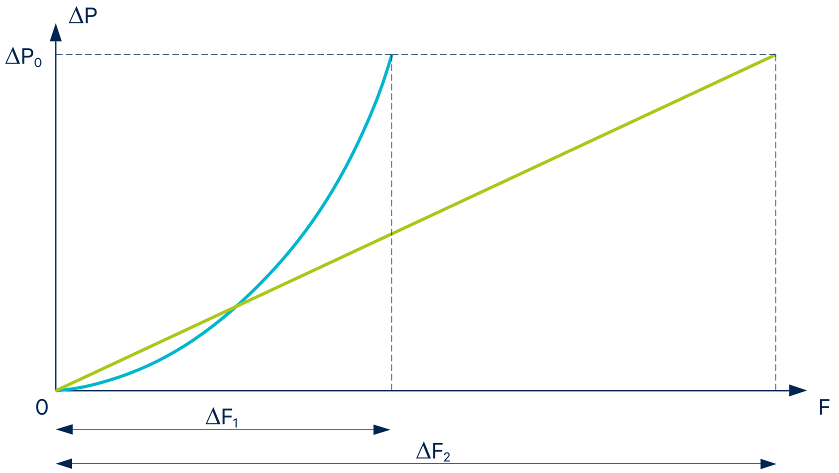

Figure 2: Characteristics for laminar (green) and orifice-like (blue) flow restrictive element.

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1.4 Barometric correction

For any thermo-anemometer type differential pressure sensor, including the LDE/LME/LMI, output signal V_{out} is proportional to gas density ρ. That is why barometric correction is required for ΔP measurements.

$$V_{out} \sim \Delta P \cdot \rho \qquad (1)$$

From Poiseuille's equation, pressure drop on a laminar restrictor ΔP is proportional to mass flow $\dot{M}$ and inversely proportional to gas density ρ:

$$\Delta P \sim [\mu L/D^4] \cdot \dot{M} \cdot 1/\rho \qquad (2)$$

From (1) and (2)

$$V_{out} \sim [\mu L/D^4] \cdot \dot{M} \qquad (3)$$

From Bernoulli's equation pressure drop on an orifice-like restrictor ΔP is proportional to mass flow in power of two $\dot{M}^2$ and inversely proportional to gas density ρ:

$$\Delta P \sim [1/D^4] \cdot \dot{M}^2 \cdot 1/\rho \qquad (4)$$

From (1) and (4)

$$V_{out} \sim [1/D^4] \cdot \dot{M}^2 \qquad (5)$$

From (3) and (5) follows that the LDE/LME/LMI sensors intrinsically require no barometric correction for mass flow measurements.

Definitions:
ΔP: pressure drop on a flow-restrictive element;
$\dot{M}$: mass flow;
ρ: gas density;
μ: gas viscosity;
L: length of a flow-restrictive element;
D: inner diameter of a flow-restrictive element.

1.5 Temperature compensation

The LDE/LME/LMI families feature an embedded temperature sensor. Depending on the application, the LDE/LME/LMI sensor can be fully temperature compensated at the factory either for mass flow or for differential pressure.

1.6 Bypass flow

A main channel restrictor's pressure/flow characteristic is usually defined without considering bypass flow and bypass flow variation from sample to sample. Thus, a smaller flow in the bypass results in better bypass/main channel split ratio and therefore higher accuracy. The amount of flow in the bypass channel is defined by a sensor's pneumatic impedance Zp [pressure per flow]. The higher the impedance, the lower the bypass flow. The pneumatic impedance of the LDE/LME/LMI families can be found in a range from 10,000s to 100,000s (Pa · s) / (ml).

For example, if a 250 Pa LDE sensor's pneumatic impedance Zp is 25,000 (Pa · s) / (ml), then the bypass flow at nominal pressure F_{250} can be found as

$$F_{250} = \Delta P / Zp = 250\ \text{Pa} / 25{,}000\ (\text{Pa} \cdot \text{s}) / (\text{ml}) = 0.01\ \text{mL/s}.$$

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2. LDE/LME/LMI features suitable for flow metering

- No temperature or barometric compensation is needed for mass flow application.
- The highest-in-class pneumatic impedance guarantees the highest immunity to contamination and the highest bypass/main channel split ratio.
- An embedded temperature sensor can be read out by the user for temperature correction in volumetric flow application (see paragraph 1.2).
- Linearized sensor output is convenient for expanding pressure and flow dynamic range by "cascading" the LDE/LME/LMI sensors. For example, a 50 Pa sensor can be read out in parallel with a 500 Pa sensor virtually without data irregularities when transitioning from sensor to sensor.

3. Application example – 30 SCCM flowmeter

3.1 Implementation

The flowmeter sample shown below is intended for air flow measurements up to 30 SCCM at a pressure drop of 250 Pa or less. The flowmeter consists of two main parts – the 250 Pa LME sensor and the laminar restrictor. The restrictor is implemented as a capillary-like pipe embedded into the LME's adapter. The adapter provides convenience and flexibility in connecting the flowmeter to a flow source.

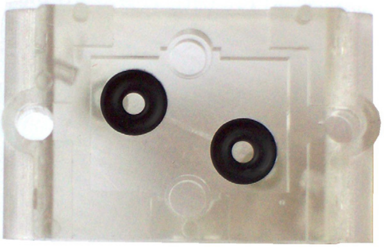

Figure 3a: 3D printed laminar flow restrictor inside transparent adapter sample for the LME sensor.

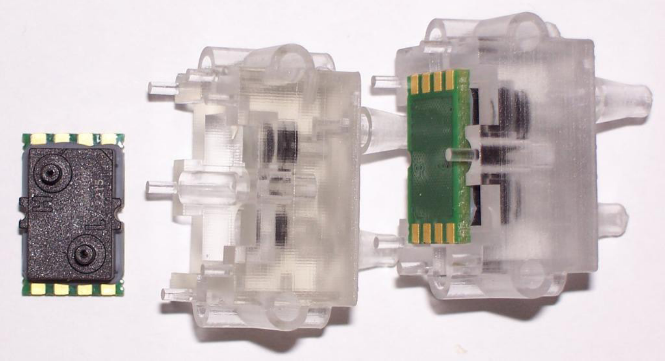

Figure 3b: LME sensor, adapter sample, and assembly.

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3.2 Evaluation result

The result of the evaluation is shown in the plot below. The flowmeter's output – analog or digital – increases linearly with the flow. The pressure drop does not exceed 250 Pa at 30 SCCM. The split ratio between bypass and main flow is in the range of 0.0001 to 0.0005.

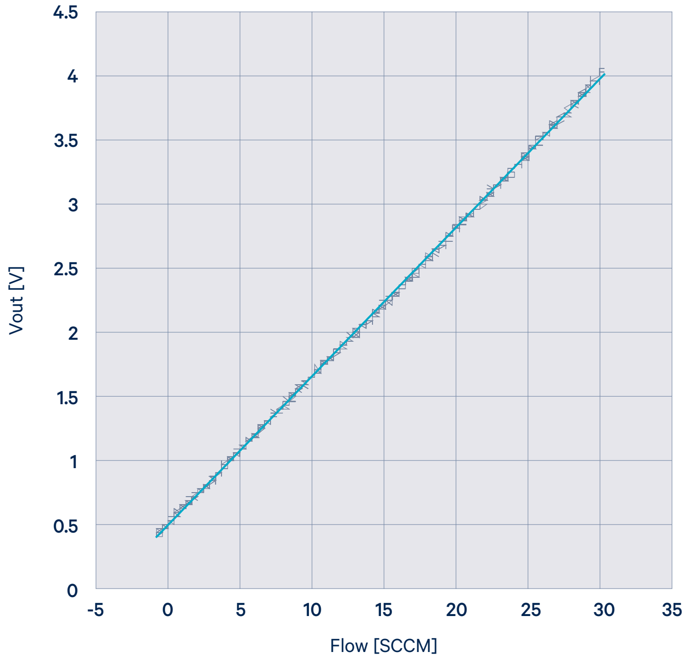

Figure 4: Output vs. flow of LME pressure sensors, t=500 ms (10,000 samples, dt=50 µs).

3.3 Expected performance

Using the LDE/LME/LMI series in bypass configuration, a SCCM level flowmeter is expected to deliver superior accuracy, stability, and power consumption in comparison to competitor products.

Device	Flow range [SCCM]	Vs [V]	Ws [mW]	Accuracy [%FS]	Offset stability [%FS]	Comp. temp. range [°C]	Pressure drop [Pa]
Competitor's high accuracy flowmeters	50, 100, 200, 400, 750	3.3 / 5	40 / 65	±7 to ±15	±0.06 per 1000h	0 ... 50	±25 to ±125
LDE/LME/LMI based mass flow meters	50, 100, 200, 400, 750	3.3 / 5	12 / 35	±1.5 to ±3	±0.05 per year	0 ... 70	±25 to ±500