Reference and Flow Conversions

Applicable to following sensors
All SFMs

Key content

- Concept of mass flow vs. volumetric flow
- Conversion between different reference conditions
- Conversion from mass-flow to volumetric-flow

Summary
This application note explains the difference between mass flow and volumetric flow.
Depending on the industry and manufacturer of flow meters, the reference conditions are different and flow values cannot be compared without converting them to the same reference conditions. The conversion between different reference conditions and from mass flow to volumetric flow under consideration of the environmental conditions of temperature, humidity and pressure are outlined in this document.

1 Introduction

Gas is a well compressible media, and the gas density therefore depends on the pressure and temperature of the gas. As such, a fixed volume of gas contains a different number of gas molecules, varying with temperature and pressure. To uniquely define a specific gas flow, which is a measure of a volume of gas per unit of time, it is necessary to reference the conditions under which the measurement is performed. Depending on the industry and the manufacturer of flow meters, these reference conditions are different and flow values can often not directly be compared without converting them to identical reference conditions.

Gas flow can either be measured in units of volumetric flow or mass flow.

Volumetric flow
Volumetric flow refers to a measured gas volume per unit of time under the referenced pressure and temperature conditions. The most common units are "liters per minute [l/min]" or "actual cubic feet per minute [acfm]".

Mass flow or standard volumetric flow
Standard volumetric flow refers to the volumetric flow at standard conditions defined for temperature and pressure. Common units are "standard liters per minute [slm]", "standard cubic centimeters per minute [sccm]" or "norm liters per minute [ln/min]".

Because standard volumetric flow is referenced to a defined temperature T and pressure p, the number of molecules n in the volume V can be calculated using the ideal gas law ($p \cdot V = n \cdot k \cdot T$). In other words, standard volumetric flow refers to the number of molecules per unit of time and therefore to the mass per unit of time. For a given gas, a sensor measuring volumetric flow at standard conditions will deliver the same readings as a mass flow sensor.

SFMxxx mass flow meters
Mass flow meters of the SFMxxx series are based on the thermal flow measurement principle and provide a mass flow output in slm, which is a mass flow unit. For example, 1 standard litre per minute (slm) means that the measured mass flow corresponds to a volumetric flow of 1 litre per minute under standard conditions. Sensirion's flow meters with a flow value in units of slm or sccm are defined at standard conditions of 20°C and 1013mbar (please refer to the specific datasheets).

Applications
In many applications mass flow is the desired quantity instead of volumetric flow. For example, in heating applications the calorimetric heating value, i.e. the number of gas molecules, is more important than the actual volumetric flow. Because of its thermal measurement principle Sensirion's SFMxxx flow meters are intrinsically mass flow meters.

In respiratory applications volumetric flow is typically of interest instead of the mass flow. The reason is that human lungs have a fixed volume and will contain a varying mass flow volume (a different number of molecules) depending on the ambient conditions such as pressure/altitude, temperature, and relative humidity. Chapter 3 explains the conversion from mass flow to volumetric flow for the SFMxxx series.

2 Conversions between Different Reference Conditions

Standard flow rate (e.g. slm) is the equivalent volumetric flow rate of the gas at the reference conditions (temperature and pressure). Although units such as slm or sccm look like a volumetric measurement they are a mass flow unit and for a given medium this corresponds to the number of molecules per unit of time.

All Sensirion flow meters with a flow output in slm or sccm are defined at the reference conditions of 20°C and 1013 mbar, for flow meters with outputs in norm liters per minute (typically SFM54xx) the reference condition is 0°C and 1013 mbar.

Mass flow rates at different reference conditions can easily be converted into each other with the following equation:

$$\boldsymbol{Q_{RC1}} = \boldsymbol{Q_{RC2}} * \left(\frac{\boldsymbol{T_{RC1}}}{\boldsymbol{T_{RC2}}}\right) * \left(\frac{\boldsymbol{P_{RC2}}}{\boldsymbol{P_{RC1}}}\right)$$

Q_{RC1} standard flow rate with reference conditions 1
Q_{RC2} standard flow rate with reference conditions 2
T_{RC1} reference temperature 1
T_{RC2} reference temperature 2
P_{RC1} reference pressure 1
P_{RC2} reference pressure 2

3 Conversions from Mass Flow to Volumetric Flow

In respiratory applications volumetric flow instead of mass flow is typically of interest. Figure 1 below depicts the change of the gas properties often encountered:

- In ventilation, the inspiratory sensor measures a gas flow at condition 0, which is then humidified and delivered to the patient at gas condition 1 (often equal to BTPS). In the absence of a humidifier, the lung would bring the gas to BTPS conditions and cause the gas to expand in the same way. Note that by humidification water molecules are added to the gas and thus the gas volume and flow are increased.

- In spirometry, ambient air is measured (condition 0) and then inhaled. Again, in the lung the gas condition is changed to BTPS (condition 1) and thus expands.

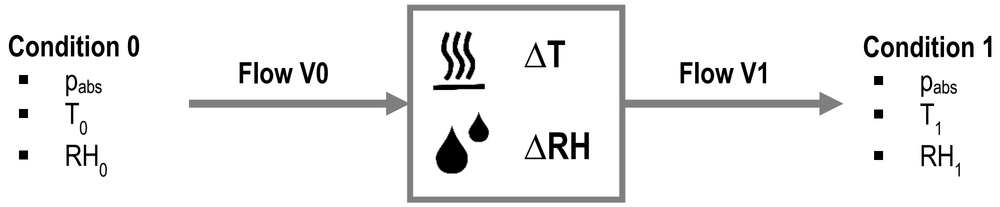

Figure 1Schematic of gas flow at various conditions including the change of temperature and humidity

3.1 General Formula for Volumetric Flow

With the following equation, the sensor reading (in slm) at one condition ("sensor") can be converted into a volumetric flow at a different condition ("target") while the gas temperature and relative humidity can change between these two conditions:

$$\dot{V} = \frac{Q}{1 + C_{H2O} * d_v(T_{sensor}, RH_{sensor})} \frac{101325}{p_{abs} - p_{H2O,target}} \frac{T_{target}}{293.15}$$

With:

$\dot{V}$	volumetric flow of (humid) air in liters/min
Q	mass flow reading of sensor in slm
p_{abs}	barometric pressure in Pa
$p_{H2O,target}$	partial pressure of water in Pa at target condition
T_x	temperature of air in Kelvin (sensor / target condition)
RH_{sensor}	actual relative humidity at sensor condition
d_v	absolute humidity in g/m^3 at sensor condition
C_{H2O}	= 0.002; experimentally determined to be around ~0.2% per g(H_2O)/m^3 of added absolute humidity.

Note: with the factor $\frac{1}{1 + C_{H2O} * d_v(T_{sensor}, RH_{sensor})}$ the sensor mass flow reading Q in slm of humid air is transformed into the corresponding a mass flow value of dry air in slm (without humidity).

For the case of **dry gases** (without humidity) the above equation simplifies to:

$$\dot{V} = Q\,\frac{101325}{p_{abs}}\,\frac{T_{target}}{293.15}$$

With:

$\dot{V}$	volumetric flow of (humid) air in liters/min
Q	mass flow reading of sensor in slm
p_{abs}	barometric pressure in Pa
T_{target}	temperature of air in Kelvin at target

The **absolute humidity** can be derived from the relative humidity and temperature with the following equation:

$$d_v(T, RH) = 216.7\left[\frac{\frac{RH}{100\%}A\ \cdot exp\left(\frac{m \cdot T}{T_n + T}\right)}{273.15 + T}\right]$$

With:

d_v	absolute humidity in g/m³
T	actual temperature in °C
RH	actual relative humidity
m	17.62
T_n	243.12 °C
A	6.112 hPa

3.2 Calculator

The excel calculator in AppNote SFM-26 “Reference And Flow Conversions Calculator” with the equations described above allows to determine the scaling factor to convert the mass flow sensor reading into the volumetric flow. This calculator can be downloaded here

Example 1: Convert Mass Flow of Dry Air to Volumetric Flow at BTPS Conditions
Considering a Sensirion mass flow sensor is positioned on the inspiratory side of a ventilator and exposed to dry wall gas at ambient temperature, e.g. T_{sensor} = 20°C and RH_{sensor} = 0%. The gas is then humidified and warmed to body core temperature, hence T_{target} = 37°C and RH_{target} = 100%. As such, water vapor is added to the dry gas and the gas temperature is increased. Both circumstances result in a volume expansion.

The scaling factor to convert the mass flow reading of the sensor to volumetric flow at BTPS conditions can be calculated based on the values above using the calculator tool in the following way:

	Temperature [°C]	Humidity [RH %]	Barometric Pressure [Pa]
Sensor Condition:	20	0	*N/A**
Target Condition: (typically BTPS)	37	100	101325

	Absolute Humidity [g/m3]	H_2O Partial Pressure [Pa]
Sensor Condition:	0.00	0.00
Target Condition:	43.78	6265.31

Compensation factor: **1.1277** — Multiplying the calibrated mass flow sensor reading with this factor results in volumetric flow at target condition

Figure 2. Conversion of mass flow at dry air condition to volumetric flow at BTPS using the calculator tool

Example 2: Convert Mass Flow of Ambient Air to Volumetric Flow
Considering the Sensirion mass flow sensor is positioned downstream of a blower and exposed to ambient air at T_{sensor} = 25°C and RH_{sensor} = 50%. To convert the measured mass flow to a volumetric flow (without additional humidification of the gas), we can simply insert T_{target} = T_{sensor} and RH_{target} = RH_{sensor} into the calculator:

	Temperature [°C]	Humidity [RH %]	Barometric Pressure [Pa]
Sensor Condition:	25	50	*N/A**
Target Condition: (typically BTPS)	25	50	101325

	Absolute Humidity [g/m3]	H_2O Partial Pressure [Pa]
Sensor Condition:	11.48	1580.03
Target Condition:	11.48	1580.03

Compensation factor: **1.0100** — Multiplying the calibrated mass flow sensor reading with this factor results in volumetric flow at target condition

Figure 3. Conversion of ambient air mass flow to volumetric flow

4 Revision History

Date	Author	Version	Changes
Jan 2021	LOEH	1.0	Initial release
Sept 2021	LOEH	1.1	Corrected factor C_{H2O} = 0.002

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