Basics of Flow measurement using Hot-film anemometer

Inhaltsverzeichnis:

1. Definitions:

1.1. Air Velocity:

Definition:

„Air Velocity describes the distance an air molecule is moving during a certain time period "

Units:

Name of unit	shift	Converted to SI - Unit m/s
Meter per second	m/s	1 m/s
Kilometer per hour	km/h	0,277778 m/s
Centimeter per minute	cm/min	$1,666667 \cdot 10^{-4}$m/s
Centimeter per second	cm/s	$1 \cdot 10^{-2}$ m/s
Meter per minute	m/min	$1,66667 \cdot 10^{-2}$ m/s
Millimeter per minute	mm/min	$1,666667 \cdot 10^{-5}$ m/s
Millimeter per second	mm/s	$1 \cdot 10^{-3}$ m/s
Foot per hour	ft/h, fph	$8,466667 \cdot 10^{-5}$ m/s
Foot per minute	ft/min, fpm	$5,08 \cdot 10^{-3}$ m/s
Foot per second	ft/s, fps	0,3048 m/s
Furlong per fortnight	furlong/fortnight	$1,66309 \cdot 10^{-4}$ m/s
Inch per second	in/s, ips	$2,54000 \cdot 1^{-2}$ m/s
Knot	kn, knot	0,514444 m/s
Kyne	cm/s	$1 \cdot 10^{-2}$ m/s
Mile per year	mpy	$8,04327 \cdot 10^{-13}$ m/s
Mile (stat) per hour	mph, mi/h	0,44704 m/s
Mile (stat) per hour	mi/min	26,8224 m/s

1.2. Amount (of Gas):

The amount of Gas „*n*“ is the number of moles of gas. $1mol = 6.023 \cdot 10^{23}$ molecules. For better understanding and its compact mathematical formulation, the properties of gases are described using an idealised model called “ideal gas”.

The amount of an ideal gas is defined using the ideal gas law:

$$p \cdot V = n \cdot R \cdot T$$

using the universal gas constant $R = 8.3145 \frac{J}{mol \cdot K}$.
Volumes V, pressure p und temperature T are state variables. They are defining the state of the gas amount *n*.

For known composition of the gas, its amount n can be substituted by its mass „m“

$$p \cdot V = m \cdot R_i \cdot T$$

using R_i als individual gas constant. It is dependent on the composition of the gas:

Gas	Air	O_2	N_2	H_2	CO_2
indiv. Gas constant R_i	287	259,8	296,8	4124	188,9

Finally the amount of gas can be detected in two different ways:

1. Weighing of the amount – measuring the mass of the amount. With known weight of one gas molecule, the amount of gas can be calculated.
   Mass, measured in *kg* or *g …*

2. Determination of the state of the gas:
   measuring of the volume *V*. With known temperature T and pressure p, the amount can be caluculated using the ideal gas law.
   Volume, measured in m^3, dm^3 or cm^3

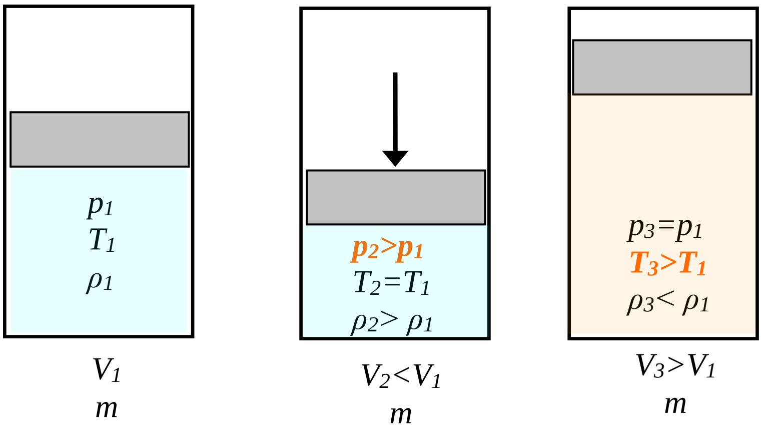
The ratio between those two quantities is defining the density *ρ*.

$$density\ \rho = \frac{mass}{volume} = \frac{m}{V} \qquad \left[\frac{kg}{dm^3}, \frac{kg}{m^3}, \frac{g}{cm^3} \right]$$

The density is a parameter of the state of the medium and is defined by the individual gas constant R_i , temperature and pressure of the medium.

$$\rho = \frac{p}{R_i \cdot T}$$

The density ρ of the gas is linearly dependent on its pressure p und its temperature T. Demonstrative, that can be shown using a cylinder whose volume can be variated by a moving piston



The system is absolutely leak proof, amount and mass of the filled medium is constant. To increase the pressure inside the cylinder the piston is pressed downwards ($p_2>p_1$), the gas is compressed, the density of the gas is increasing, the volume is decreasing. On the other hand, by heating the gas inside the cylinder ($T_3>T_1$), the density of the gas is decreasing and the volume is increasing!

Summary:
The mass of a gas with known composition is a direct measure for its amount. The volume is just defining the amount of a gas in combination with its temperature and pressure, but is independent from its composition!

To get a „temperature- and pressure independent volumetric-quantity “, the measured volume is recalculated to the volume which would be measured at standardized conditions.

This standardized volume $V_{Standard}$ is a volumetric quantity independent from composition, pressure and temperature of the gas.

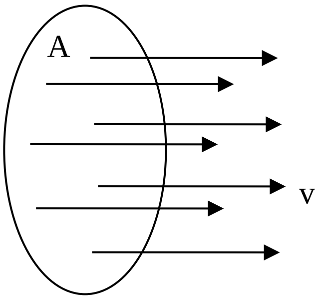
Standard conditions acc. DIN 1343:

standard temperature = 0°C = 273,15 K
standard pressure = 101325 Pa = 1,01325 bar

Standard volume:

$$V_{standard} = \frac{absolut\ pressure[bar] \cdot 273{,}15\,K}{(273{,}15 + temperature[°C]) \cdot 1{,}01325\,bar}$$

1.3. Flow



Flow defines the number of Gas-molecules streaming through the surface A during a certain time- period.

The quantities for flow are based on the different quantities for an amount of gas: mass, volume and standard volume

1.3.1. Mass flow rate

The Mass flow rate is defining the amount of a fluid with known composition flowing through a surface A in a certain time-periode.

$$\dot{m} = \frac{Mass}{time} = \frac{m[kg, g]}{t[h, s, \min]}$$

Name of unit	shift	Converted to SI - Unit kg/s
Kilogramm per second	kg/s	1 kg/s
Kilogramm per minute	kg/min	0,01666667 =1/60 kg/s
Kilogramm per hour	kg/h	2,7778*10-4 = 1/3600 kg/s
Gramm per second	GRPS (g/s)	10-3 kg/s
Gramm per minute	GRPM (g/min)	1,666667*10-5 kg/s
Gramm per hour	GRPH (g/h)	2,7778*10-7 kg/s
Pound per second	LBPS	0,453592370 kg/s
Pound per minute	LBPM	7,55987*10-3 kg/s
Pound per hour	LBPH	1,26*10-4 kg/s

1.3.2. Volumetric flow rate

The volumetric flow rate is defining the volume of a fluid for the present state, represented by temperature and pressure, streaming through the surface A in a certain time-periode.

$$\dot{V} = \frac{volume}{time} = \frac{m^3[m^3, l]}{t[h, s, \min]}$$

Name of unit	shift	Converted to SI - Unit m^3/s
Cubicmeter per second	m^3/s	1 m3/s
Cubicmeter per minute	m^3/min	0,01666667 =1/60 m3/s
Cubicmeter per hour	m^3/h	2,7778*10-4 = 1/3600 m3/s
Cubicdezimeter per second	dm^3/s	10-3 m3/s
Cubiccentimeter per second	CCS (cm^3/s)	10-6 m3/s
Cubiccentimeter per minute	CCM (cm^3/min)	1,666667*10-8m3/s
Litre per second	LPS (l/s)	10-3 m3/s
Litre per minute	LPM (l/min)	1,666667*10-5 m3/s
Litre per hour	LPH (l/h)	2,77778*10-7 m3/s
Millilitre per second	ml/s	10-6 m3/s
Millilitre per minute	ml/min	1,666667 *10-8 m3/s
Cubicfeet per second	CFH (ft^3/s)	2,83168*10-2 m3/s
Cubicfeet per minute	CFM (ft^3/min)	4,71947*10-4 m3/s
Gallons per minute (GB)	GPM	7,57682*10-5 m3/s
Gallons per minute (US)	GPM	7,34147*10-5 m3/s

1.3.3. Standard volumetric flow rate

Standard volumetric flow rate is independent from state and composition.

$$\dot{V}_{standard} = \frac{standard\ volume}{time} = \frac{V_{standard}[Nm^3, Ncm^3]}{t[h, s, \min]}$$

Name of unit	shift	Converted to SI - Unit Nm^3/s
Norm-Kubikmeter pro Sekunde (German)	Nm^3/s	1 Nm^3/s
Standard Cubicmeter per second	SCMS (Sm^3/s)	1 Nm^3/s
Standard Cubiccentimeter per second	SCCS (Scm^3/s)	10^{-6} Nm^3/s
Standard cubiccentimeter per minute	SCCM (Scm^3/s)	$1{,}666667*10^{-8}$ Nm^3/s
Standard Litre per second	SLPS (Sl/s)	10^{-3} Nm^3/s
Standard Litre per minute	SLPM (Sl/min)	$1{,}666667*10^{-5}$ Nm^3/s
Standard Litre per hour	SLPH (Sl/h)	$2{,}77778*10^{-7}$ Nm^3/s
Standard Cubicfeet pro second	SCFH (ft^3/s)	$2{,}83168*10^{-2}$ Nm^3/s
Standard Cubicfeet pro Minute	SCFM (ft^3/min)	$4{,}71947*10^{-4}$ Nm^3/s

2. Flow formulas

Volume flow is the direct combination of the surface A, the fluid is streaming through with its average velocity.

Volumetric flow rate = average velocity · flow surface

$$\dot{V}[m^3/s] = \bar{v}[m/s] \cdot A[m^2]$$

To calculate the standard volume flow it is necessary to measure actual pressure and temperature.

Standard volumetric flow rate = volumetric flow rate at standard conditions

$$\dot{V}_{\text{standard}}[Nm^3/s] = \dot{V}[m^3/s] \cdot \frac{\mathrm{p}[bar] \cdot 273{,}15\,K}{(273{,}15 + \mathrm{T}[°C]) \cdot 1{,}01325\,bar}$$

With known density of the fluid (Air) at standard conditions it is possible to calculate the mass flow.

Mass flow rate = standard volumetric flow Air density at 0°C and 1,01325 bar

$$\dot{m}[kg/s] = \dot{V}_{s\tan dard}[Nm^3/s] \cdot 1{,}292[kg/Nm^3]$$

3. Flow measurements using E+E Hotfilm anemometer:

The measurement principle of a hot-film anemometer is to measure the number of molecules which are streaming over the heater sensor, and so conduct heat.
With rising air pressure, the density of the gas is increasing and with the same velocity more molecules are streaming over the sensor. So, to measure the air velocity of the molecules at any pressure, this pressure influence has to be corrected.

At E+E all Air Velocity Transmitter are calibrated at Standard Pressure of 1,01325 bar. For diverging air pressures from 1,01325 bar, that influence has to be corrected.

Air velocity:

$$v[m/s] = v_{Transmitter}[m/s] \cdot \frac{1{,}01325\,bar}{p[bar]}$$

The temperature also has a small influence on the heat transfer from the sensor.
E+E Transmitters have implemented internal temperature compensations to correct that influence.
By measuring the average air velocity in a Tube and with known cross section surface A, the volume flow can be calculated.

Volumetric flow rate:

$$\dot{V}[m^3/s] = A[m^2] \cdot v_{Transmitter}[m/s] \cdot \frac{1{,}01325\,bar}{p[bar]}$$

In most industrial applications the volumetric flow rate at standard conditions has to be measured. In that applications the E+E Hotfilmsensor and its calibration at standard pressure shows its main advantages.

Because of the opposed pressure influence of sensor and conversion of volumetric-flow to standard-volumetric flow, the E+E Hotfilm-Sensors measure standard volumetric flow and mass flow independent to pressure.

Standard volumetric flow rate:

$$\dot{V}_{\mathrm{standard}}[Nm^3/s] = A[m^2] \cdot v_{\mathrm{Transmitter}}[m/s] \cdot \frac{273{,}15\,K}{(273{,}15 + \mathrm{T}[°C])}$$

Mass flow rate:

$$\dot{m}[kg/s] = A[m^2] \cdot v_{Transmitter}[m/s] \cdot \frac{273{,}15\,K}{(273{,}15 + \mathrm{T}[°C])} \cdot 1{,}292[kg/Nm^3]$$