Particle and flow measurements

Workshop HumanIC | July 1 — 4, 2025

Julia Lange, M.Sc.

Agenda

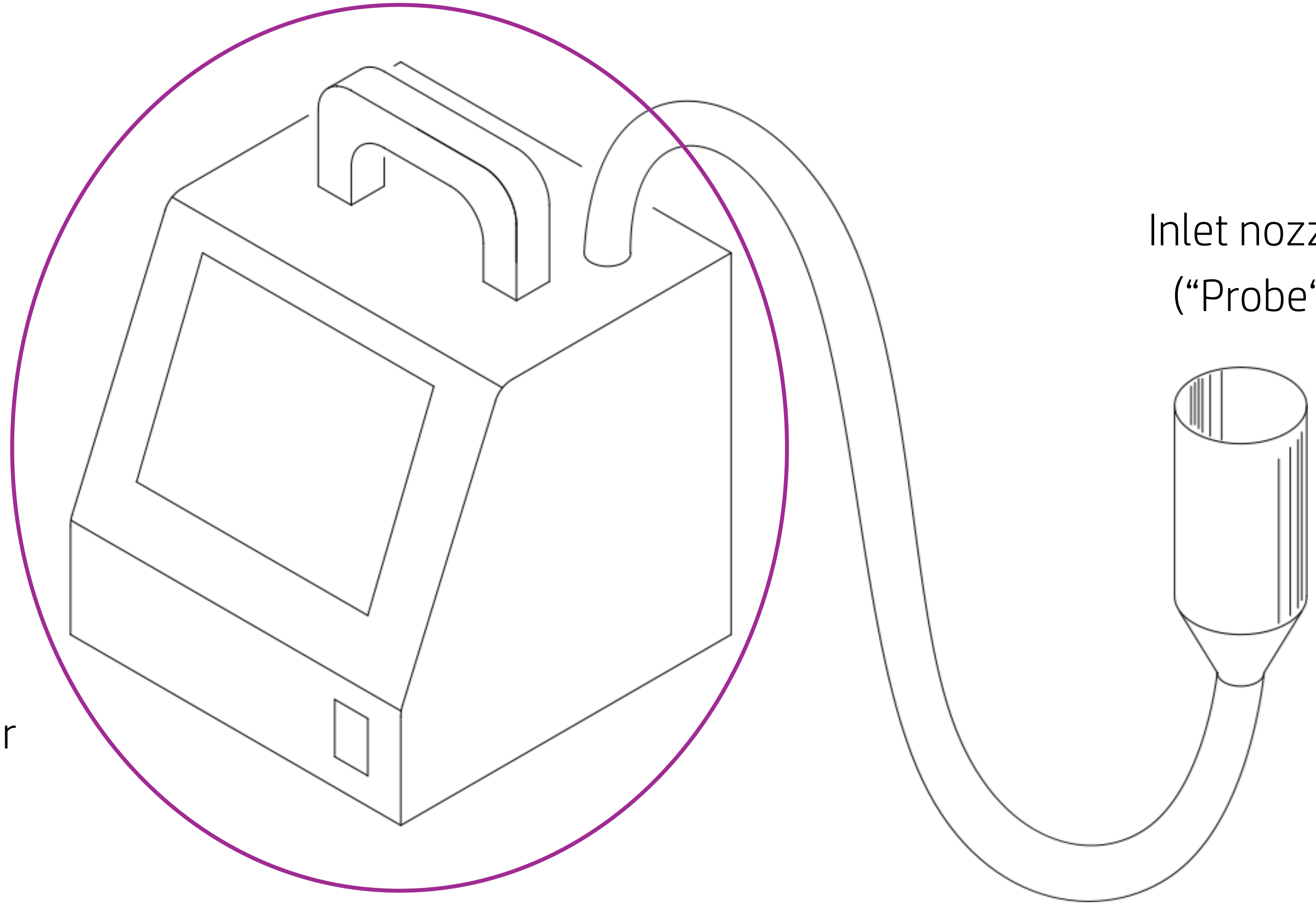
1. Particle measurements
   - 1.1 Particle Counter
   - 1.2 Coincidence
   - 1.3 Dilution System
   - 1.4 Particle Deposition in the Tube
   - 1.5 Isokinetic Sampling

2. Flow measurements
   - 2.1 Velocities
   - 2.2 Laser Doppler Anemometry
   - 2.3 Volume Flows and Pressures
   - 2.4 Turbulence intensity
   - 2.5 Measurement Uncertainty

Agenda

Particle measurements

Essential components



Particle measurements

Purpose

Particle measurement for the determination of:

- Cleanroom classification
- Room recovery time t ($\frac{C(t)}{C_0} = \frac{1}{100}$)
- Filter separation efficiency
- Filter leakage testing
- Continuous monitoring

Measurement tasks:

- Determination of **particle count** ➝ **particle counting**
- Determination of **particle sizes** ➝ **particle measurement**

Image source: (mt, 2023)

Particle measurements
Measurement methods

Different methods depending on particle size:

Cleanroom technology (0.1 - 10 µm)

- Light-scattering particle counter or aerosol photometer
- Principle: Measurement of light scattering pulses caused by particles
- Detection of **particle count** and/or **size**

Smallest particles (< 0.1 µm)

- Condensation particle counter (CPC)
- Principle: enlargement of particles by condensation on their surface
- actual particle size cannot be measured

Particle measurements

Light-scattering particle counter

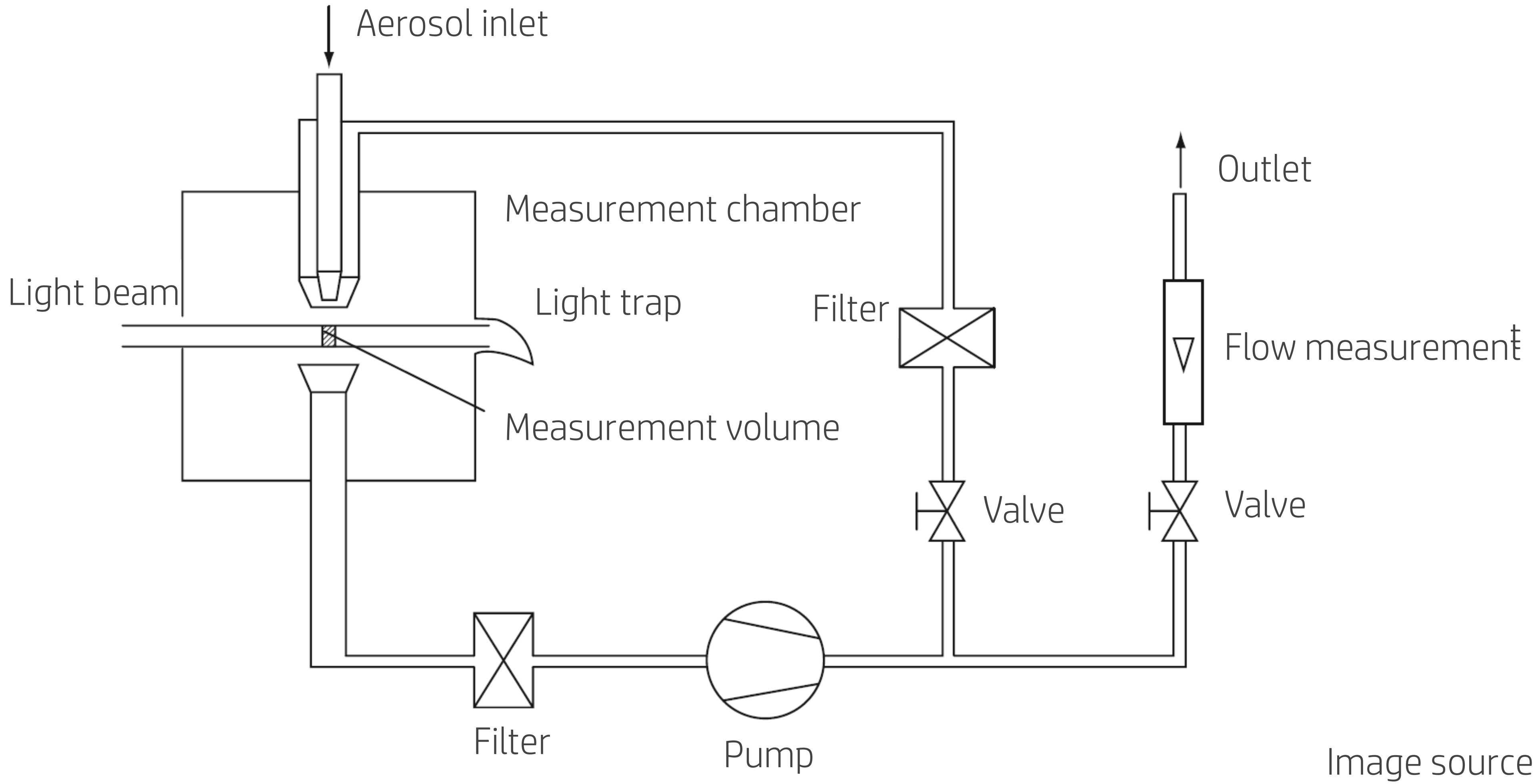
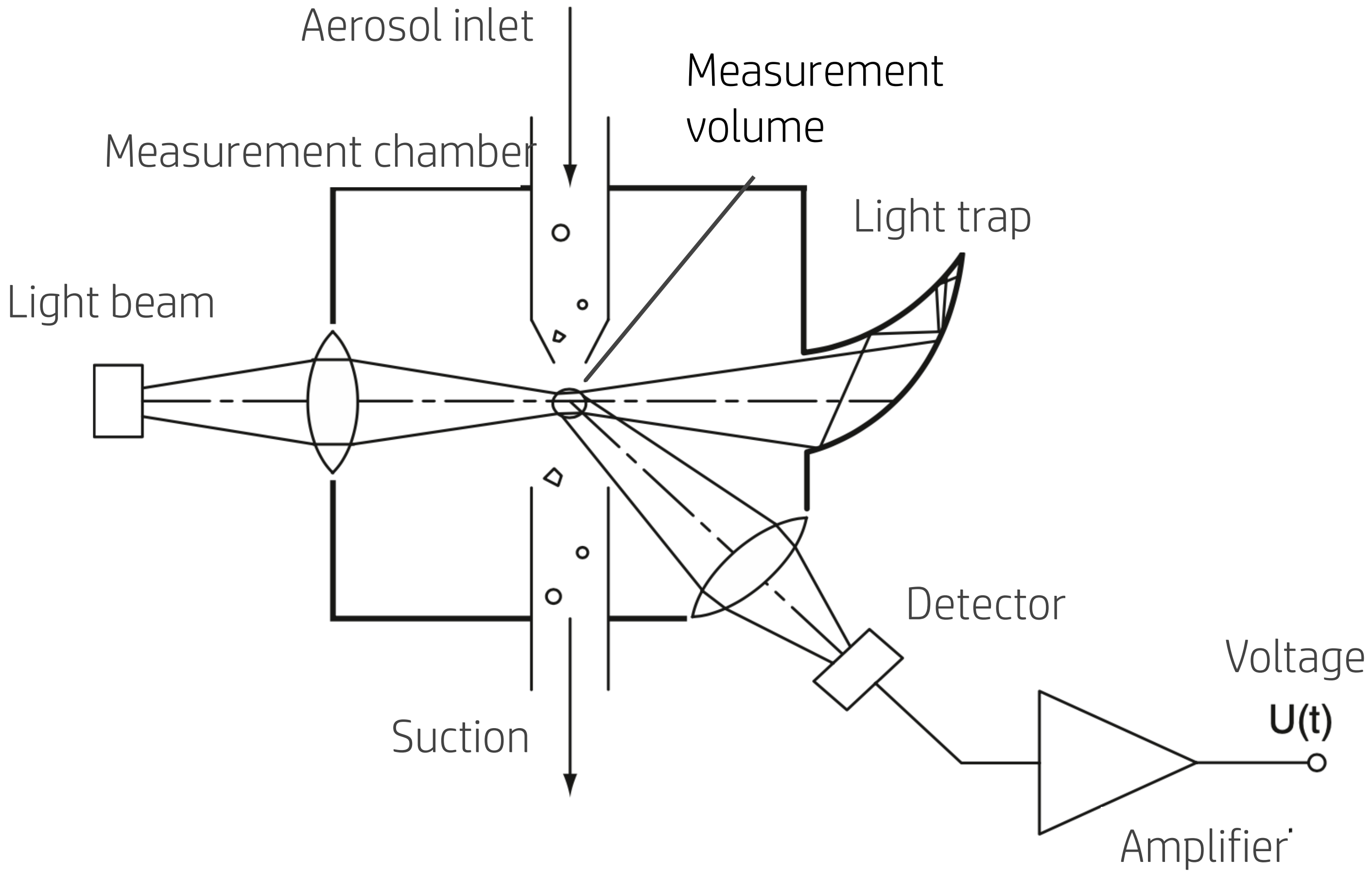


Image source: (Gail 2012)

Light-scattering particle counter

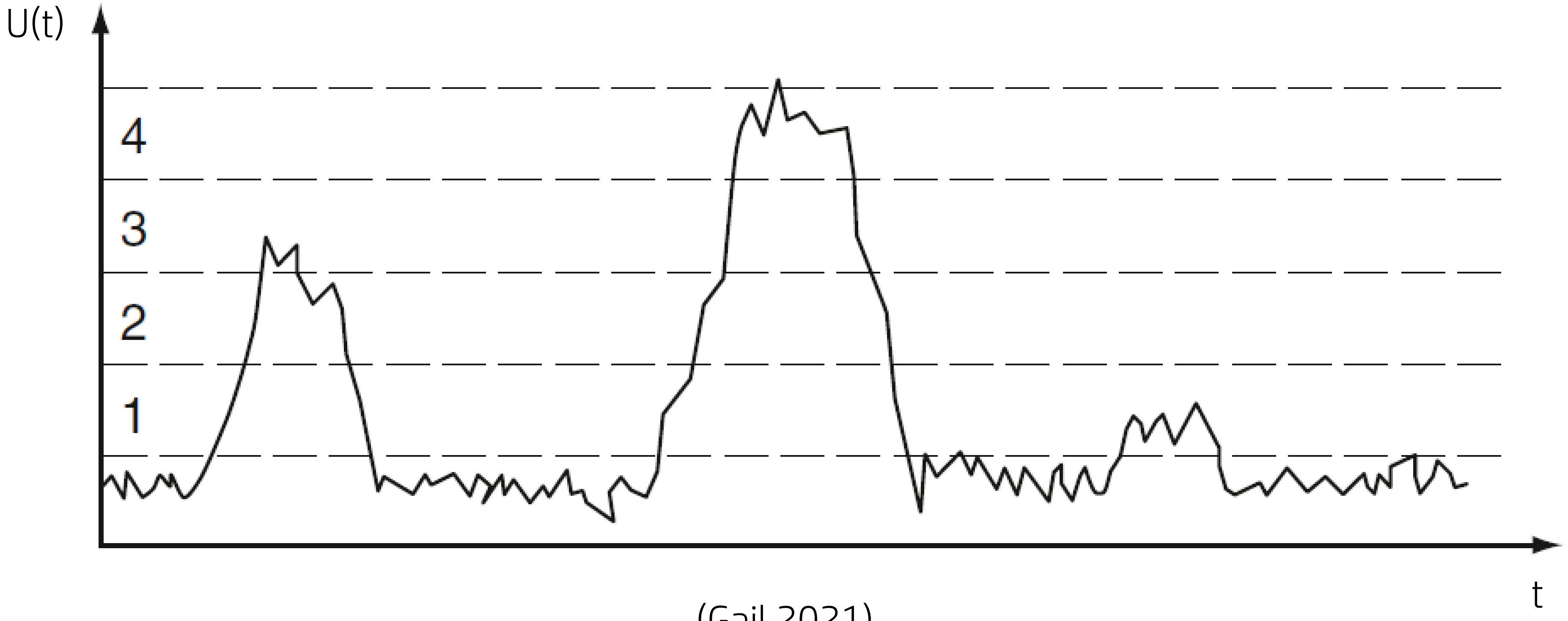


(Gail 2012)

Light-scattering particle counter

Voltage output of the sensor

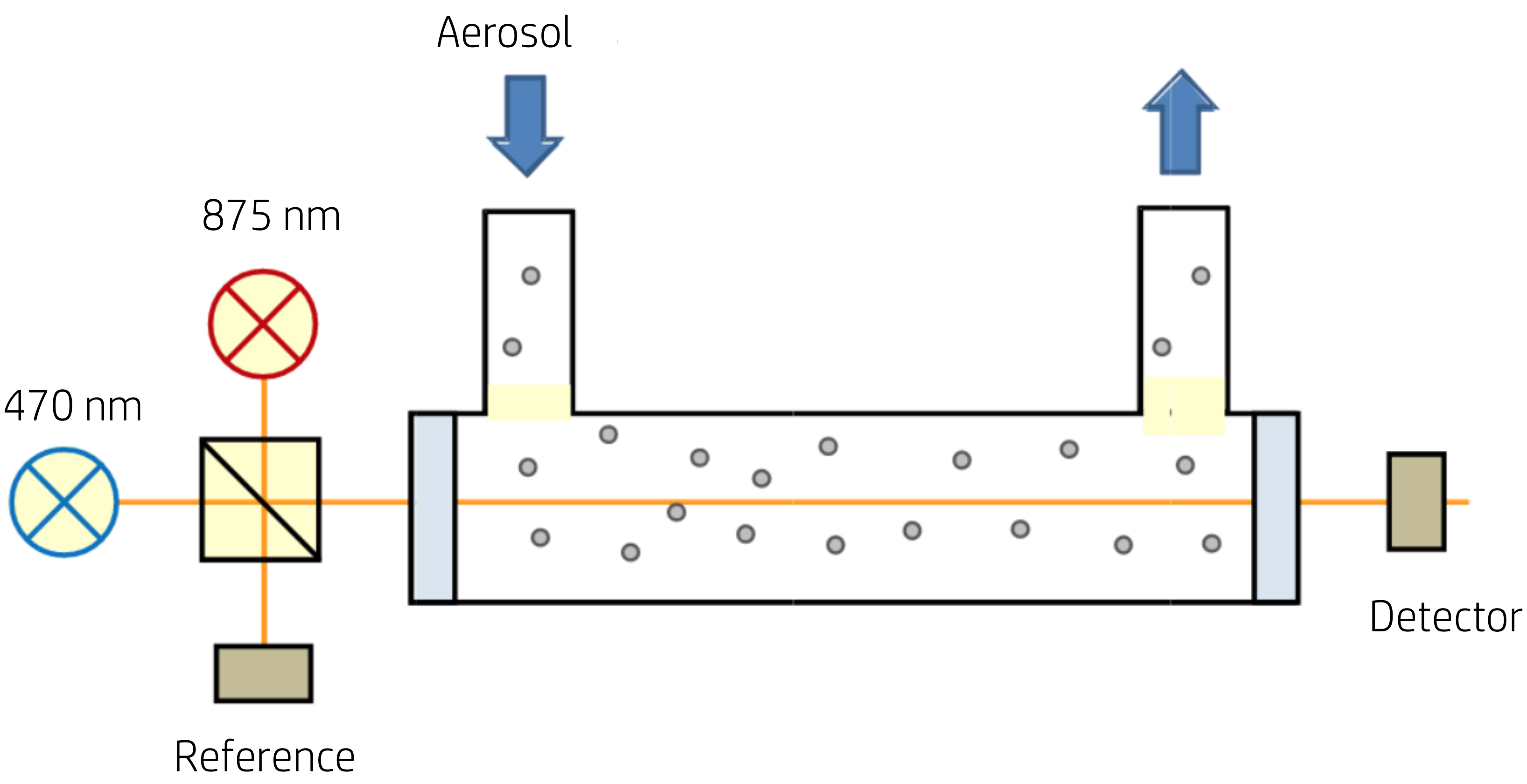
Signal at amplifier output (example):



(Gail 2021)

Aerosol photometer

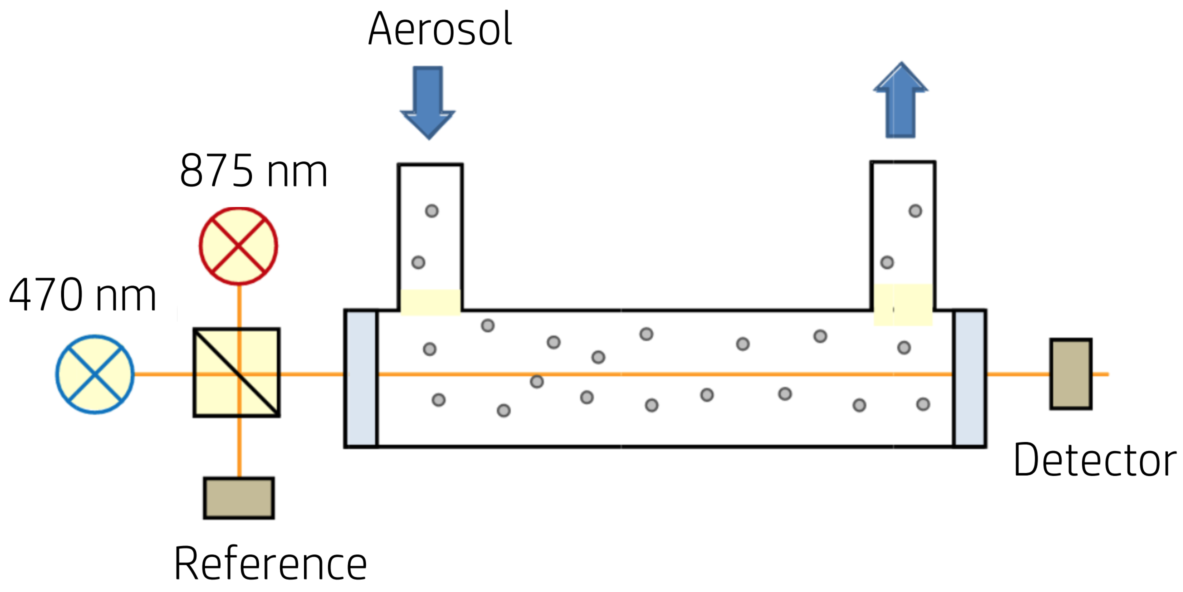
Measurement principle of the PAP 610 by Topas



(Topas, PAP 610)

Aerosol photometer

- simultaneous detection of multiple particles
- light scattering and extinction (absorption)
- two wavelengths
- two parallel measurement paths
- reduced measurement uncertainty
- suitable for high particle concentrations

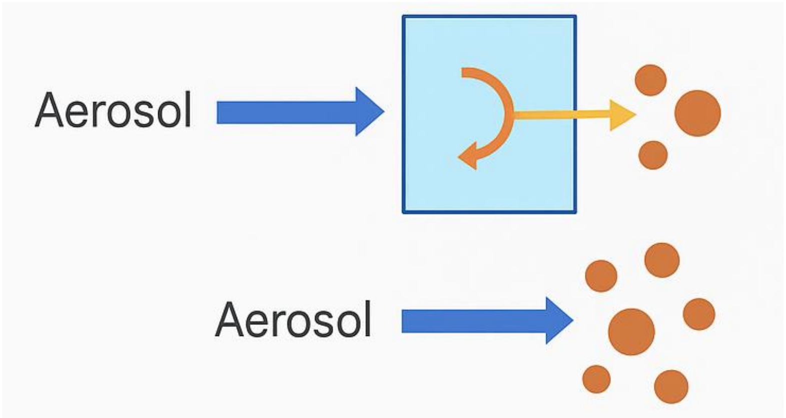


(Topas, PAP 610)

Comparison particle counters

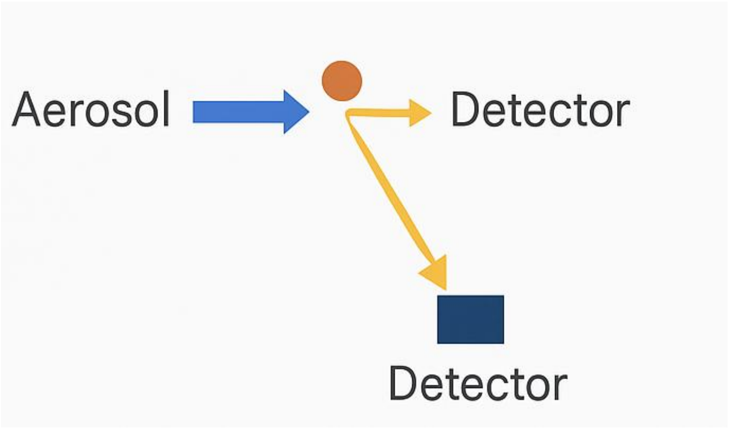
Aerosol Photometer

- measures forward-scattered light in an optical chamber
- analyzes light scattering and extinction (absorption)
- determines aerosol mass concentration



Light Scattering Particle Counter (LSAPC)

- detects and counts individual airborne particles
- determines particle size (optical equivalent diameter)
- measures aerosol number concentration



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Coincidence

Precondition for the measurement principle of the scattered light particle counter:

- one particle within the measurement volume
- signal processing completed

Coincidence:

- multiple particles are detected simultaneously

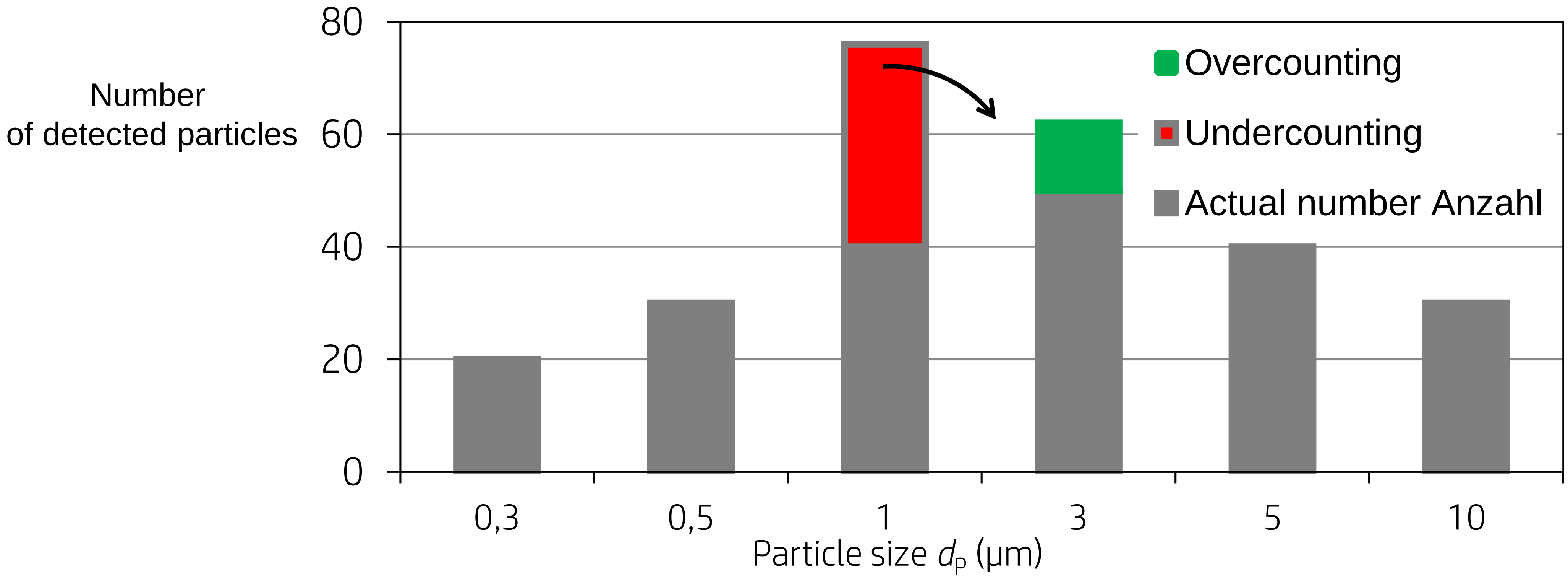
Consequences:

- reduced particle count distribution
- particle distribution with an overly large average diameter
- contamination in the particle counter and aerosol transport system

Coincidence

Example: 3 x 1 μm particles ⟶ detected as 1 x 3 μm

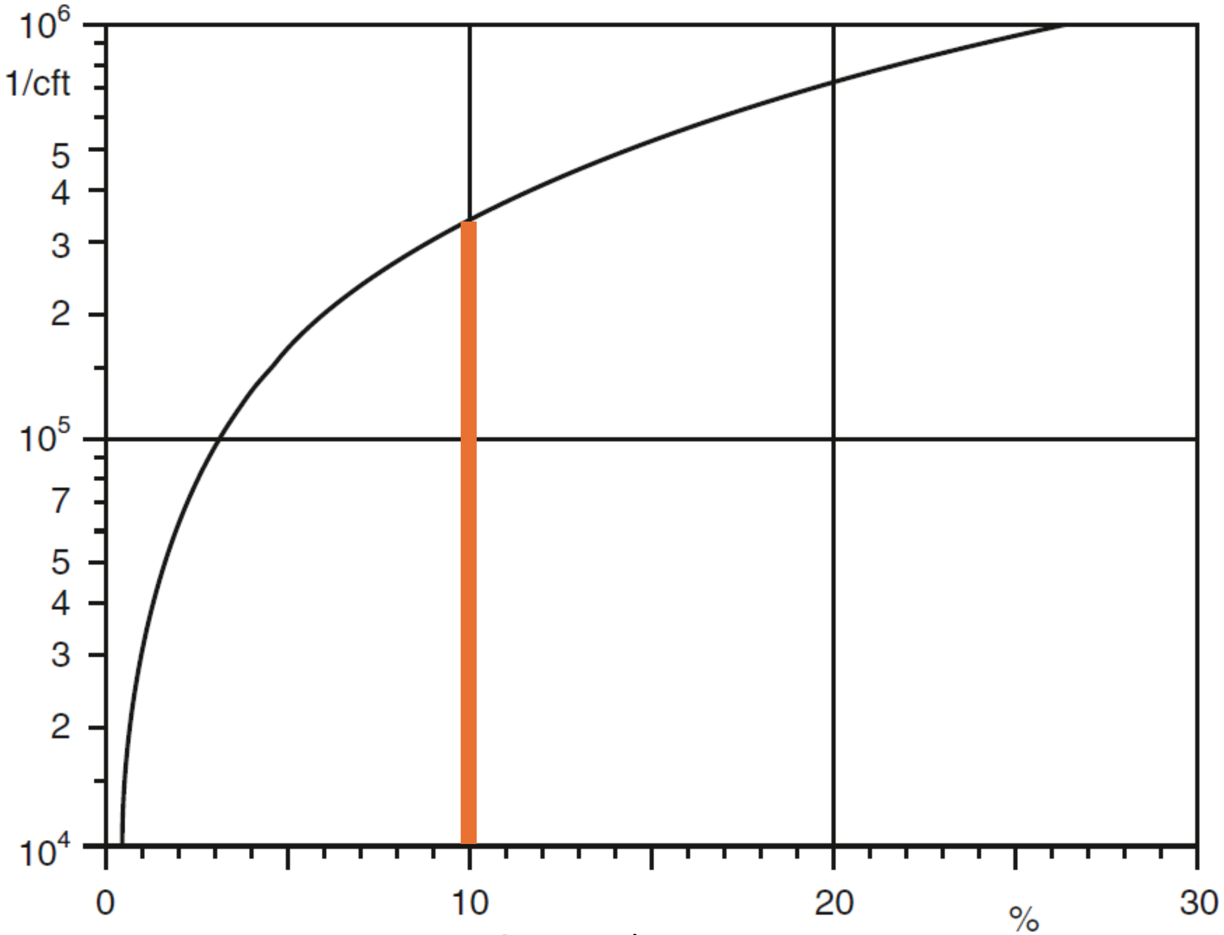
Consequence: Undercounting, oversized mean diameter



Coincidence

Coincidence limit: device-specific!

Maximum concentration



Coincidence error

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Dilution System

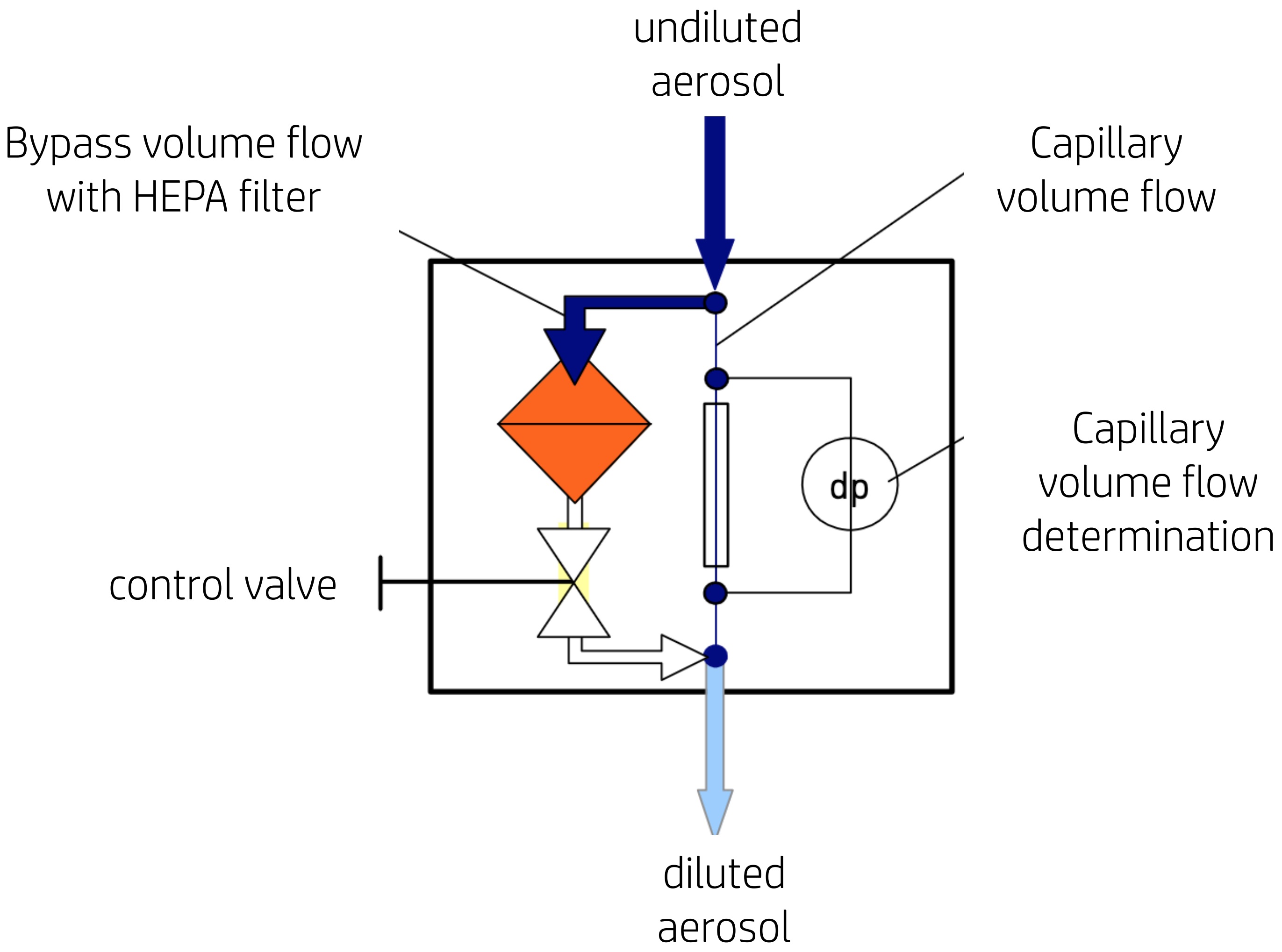
Solution for Coincidence: Dilution

- If particle concentrations exceed the coincidence limit, dilute the sample.
- Typical dilution ratios: 1:10 or 1:100
- Higher dilution levels can be achieved by cascading multiple dilution steps.

Dilution system
(Topas, DIL 554)

Dilution System

Principle



(Topas, DIL 554)

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    1.4 Particle deposition in the tube
    1.5 Isokinetic Sampling
    1.6 Laser Doppler Anemometry

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    2.1 Velocities
    2.2 Volume Flows and Pressures
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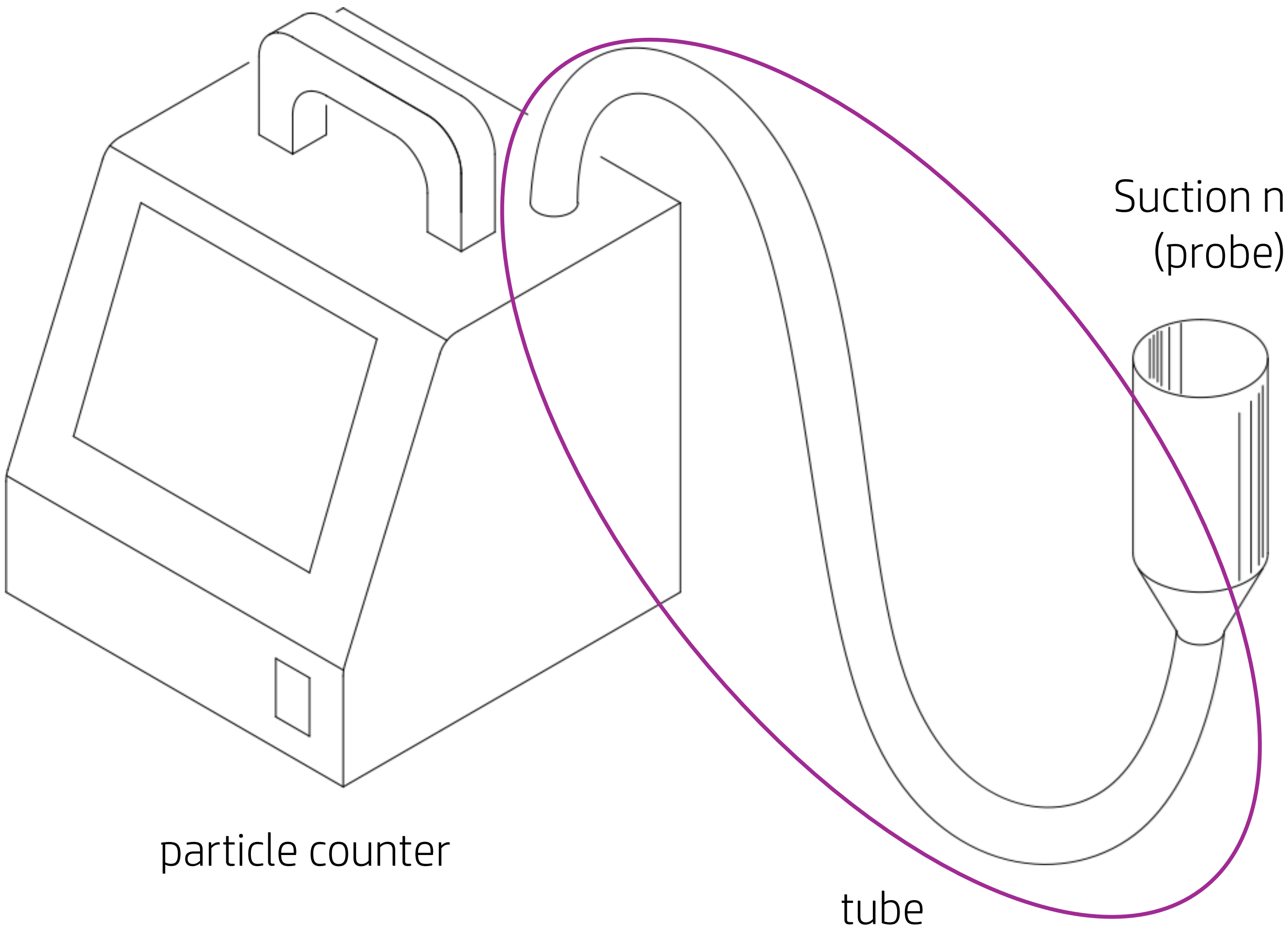
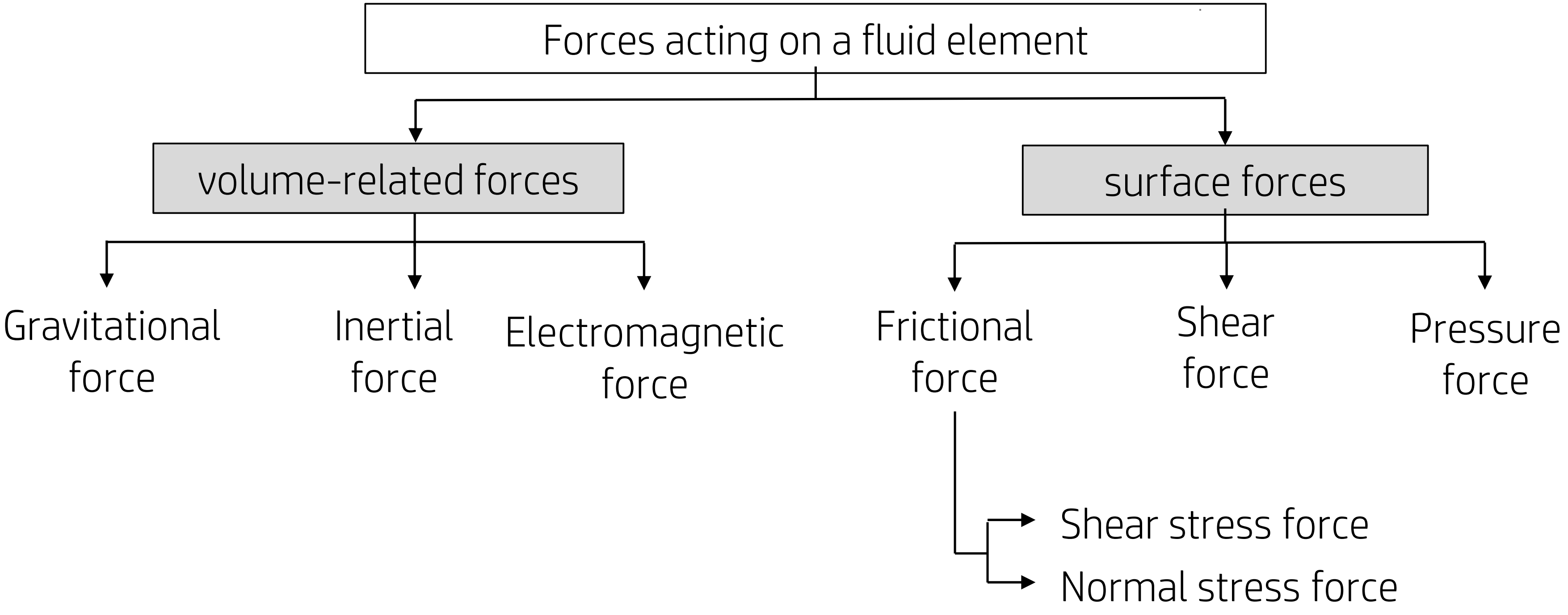
Essential components



Particle loss in the tube

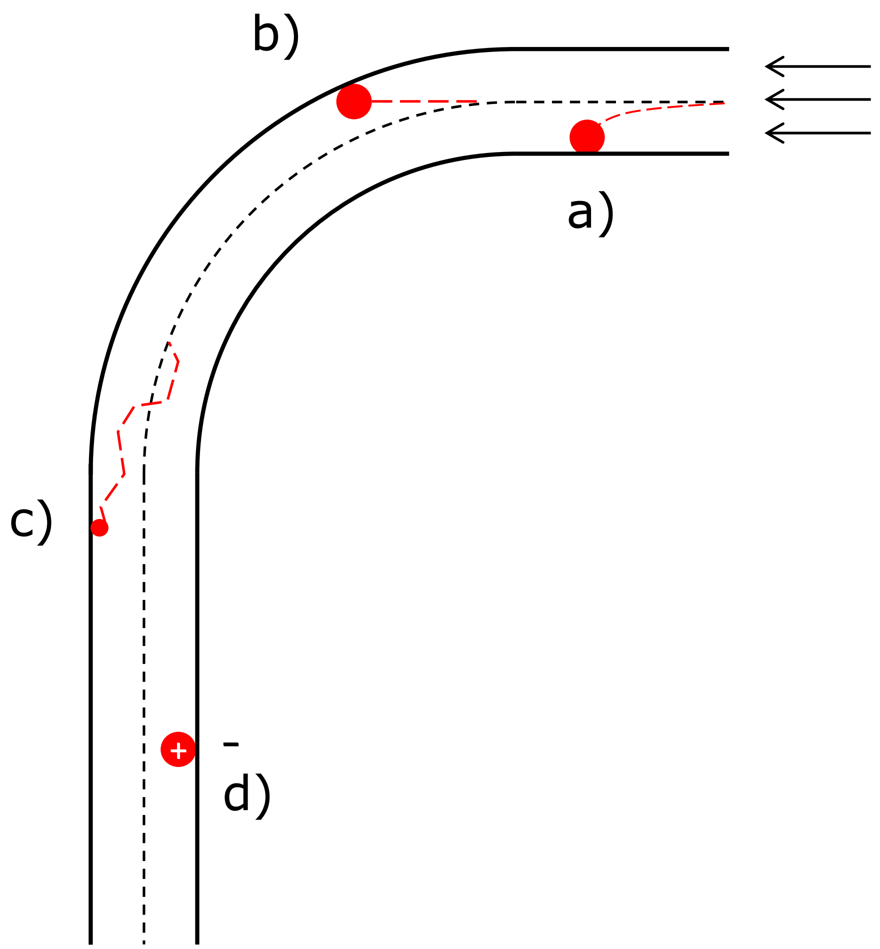


A/V ratio: The surface-to-volume ratio determines whether body or surface forces dominate.

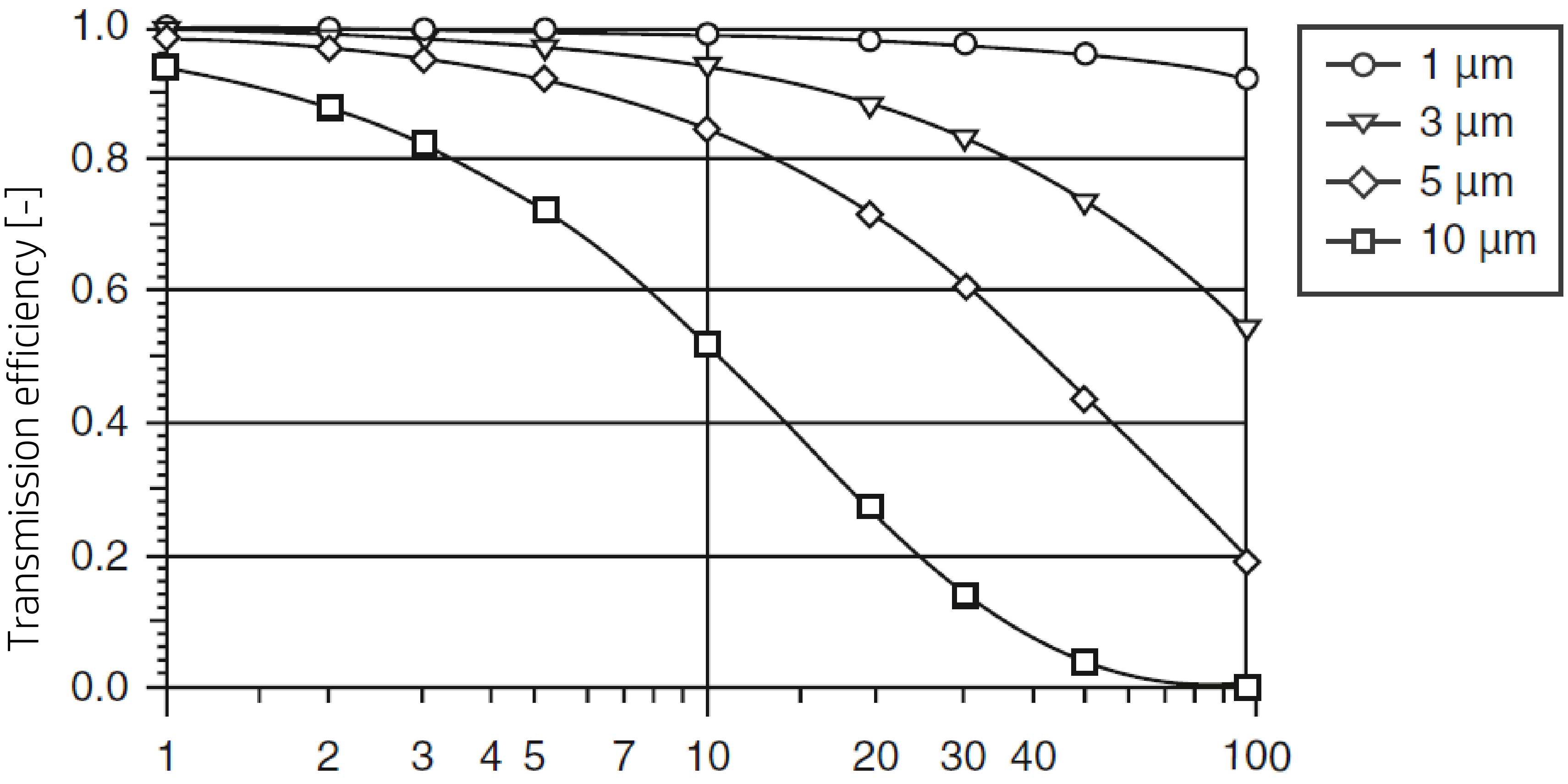
(Ghaib, 2019)

Particle loss in the tube

- Large particles
  - a) Sedimentation
  - b) Inertia
- Small particles
  - c) Diffusion effect due to Brownian motion
- Electrostatically charged particles
  - d) Electrostatic attraction (Coulomb force)



Particle loss in the tube



Tube length [m]

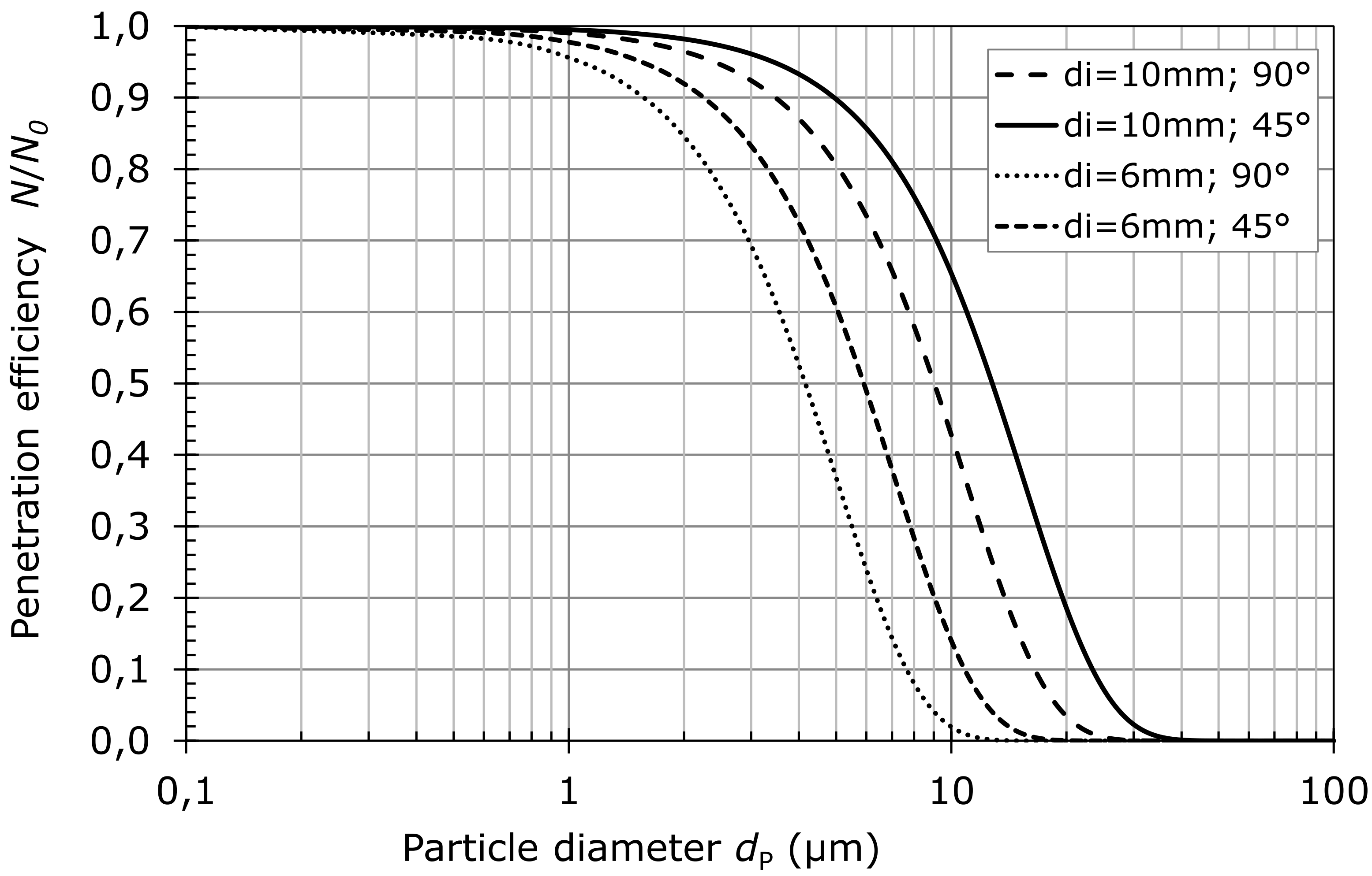
Turbulent flow at $d_i \leq 14{,}4\ mm$

Tube: $d_i = 10\ \mathrm{mm}, \dot{V} = 28{,}3\,\frac{\mathrm{l}}{\mathrm{min}}$

d_i: internal diameter

$\dot{V}$: Volume flow

Particle deposition in the pipe bend



(Hinds 1999)

Particle deposition in the pipe bend

Remote Particle Counters

- No display
- No internal pump
- No sampling tube before measurement
- Multiple counters can be connected to a single evaluation unit

(TSI, 2023)

Particle deposition in the pipe bend

Summary

Prevention measures:

- short tubing
- straight tubing layout
- electrically conductive tubing material

- Alternative: remote particle counter

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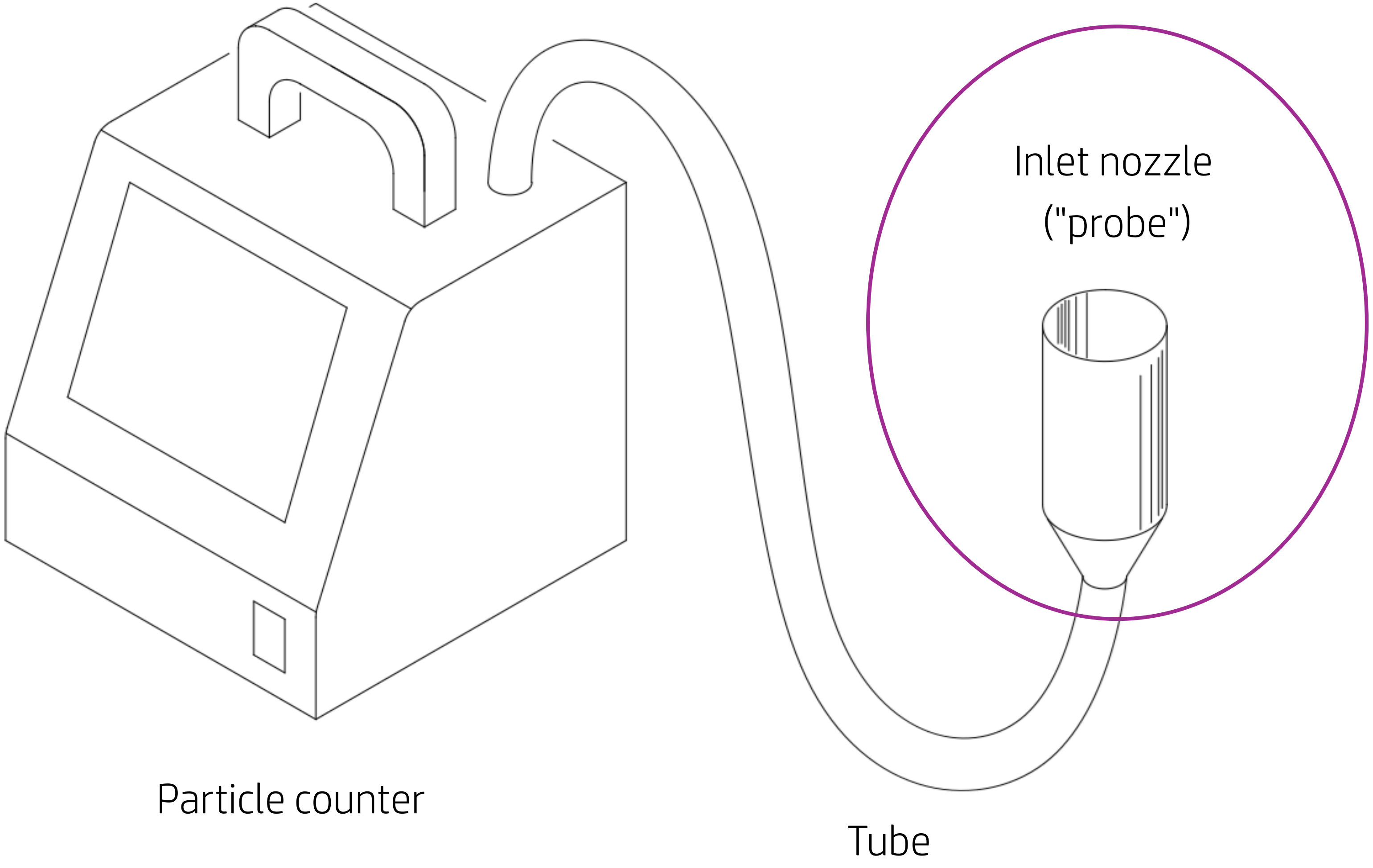
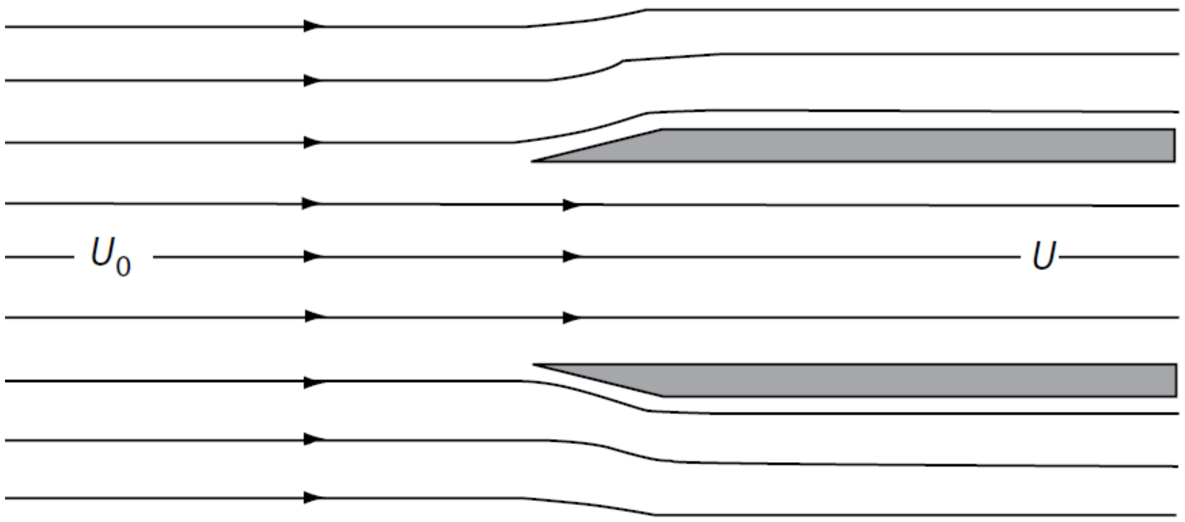
Particle measurements

Isokinetic sampling



Isokinetic sampling



$U_0 = U$

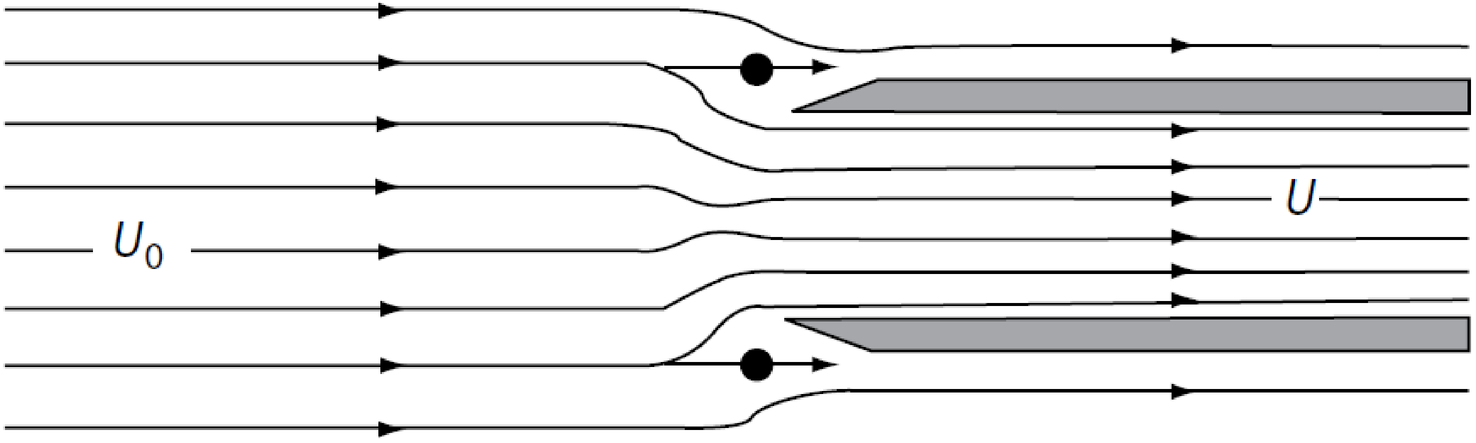
U_0 ... ambient flow velocity

U ... inlet flow velocity

(Tränkler und Reindl 2014)

Super-isokinetic sampling

(Tränkler und Reindl 2014)

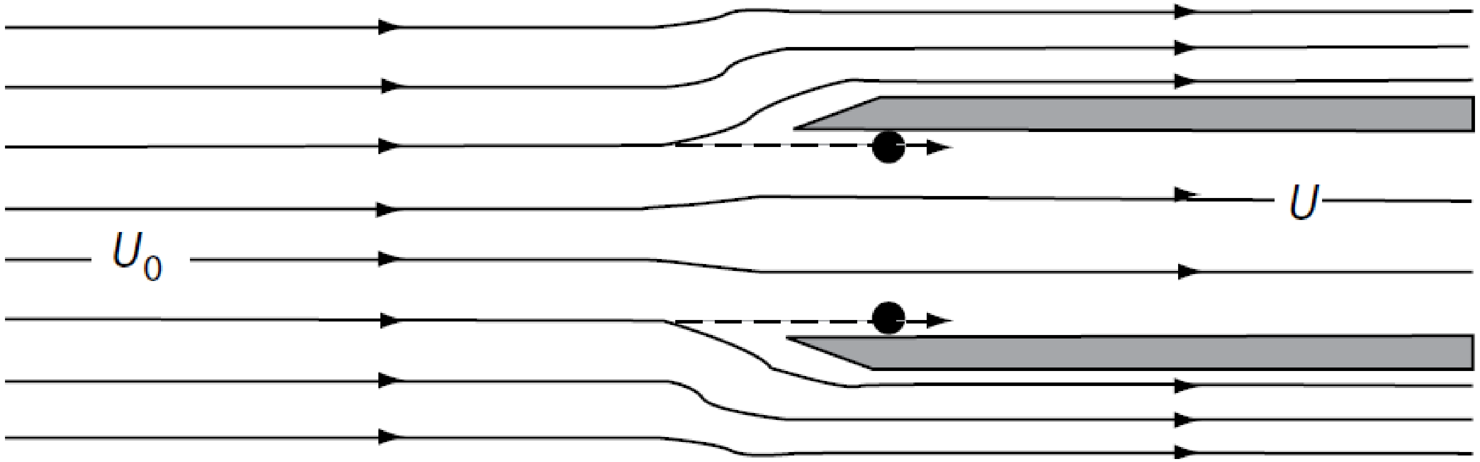


$$U_0 < U$$

U_0 ... ambient flow velocity

U ... inlet flow velocity

Sub-isokinetic sampling



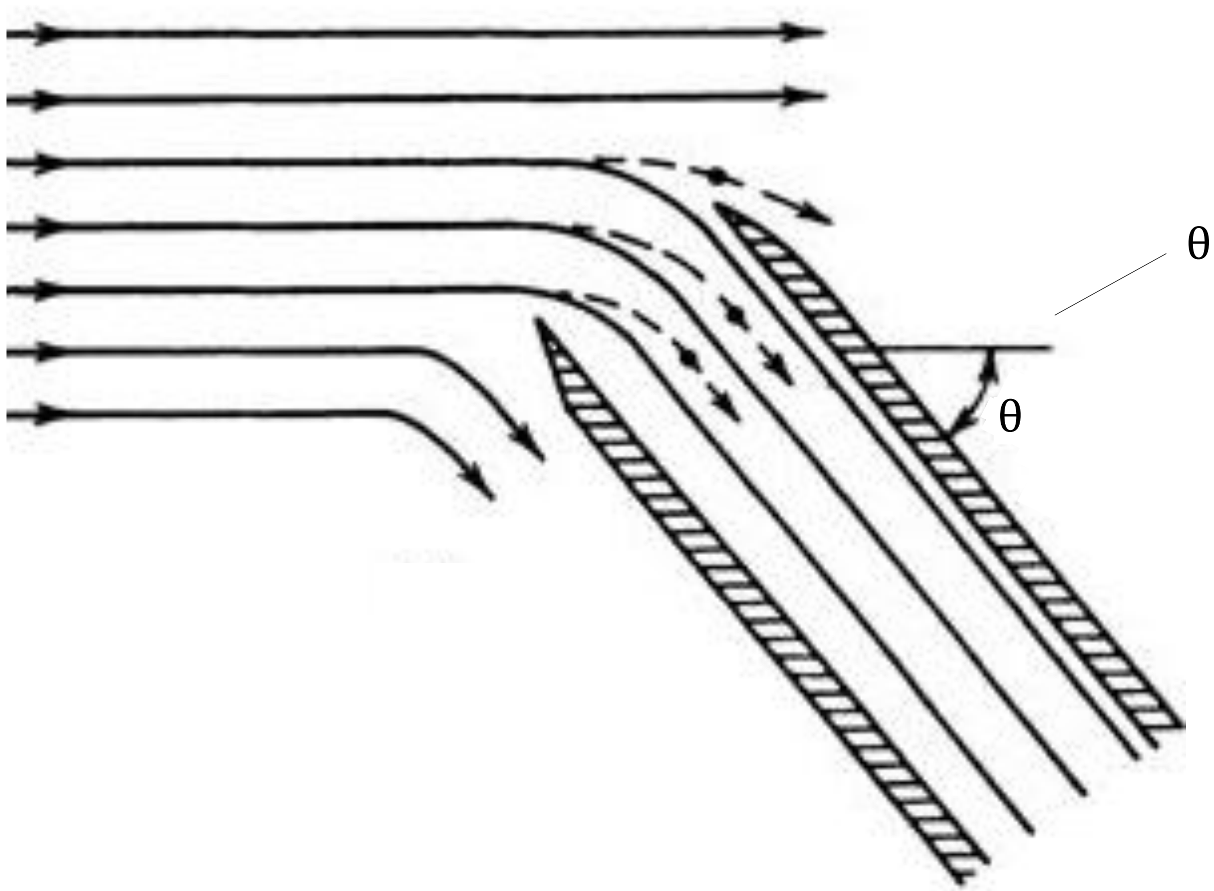
$$U_0 > U$$

U_0 ... ambient flow velocity

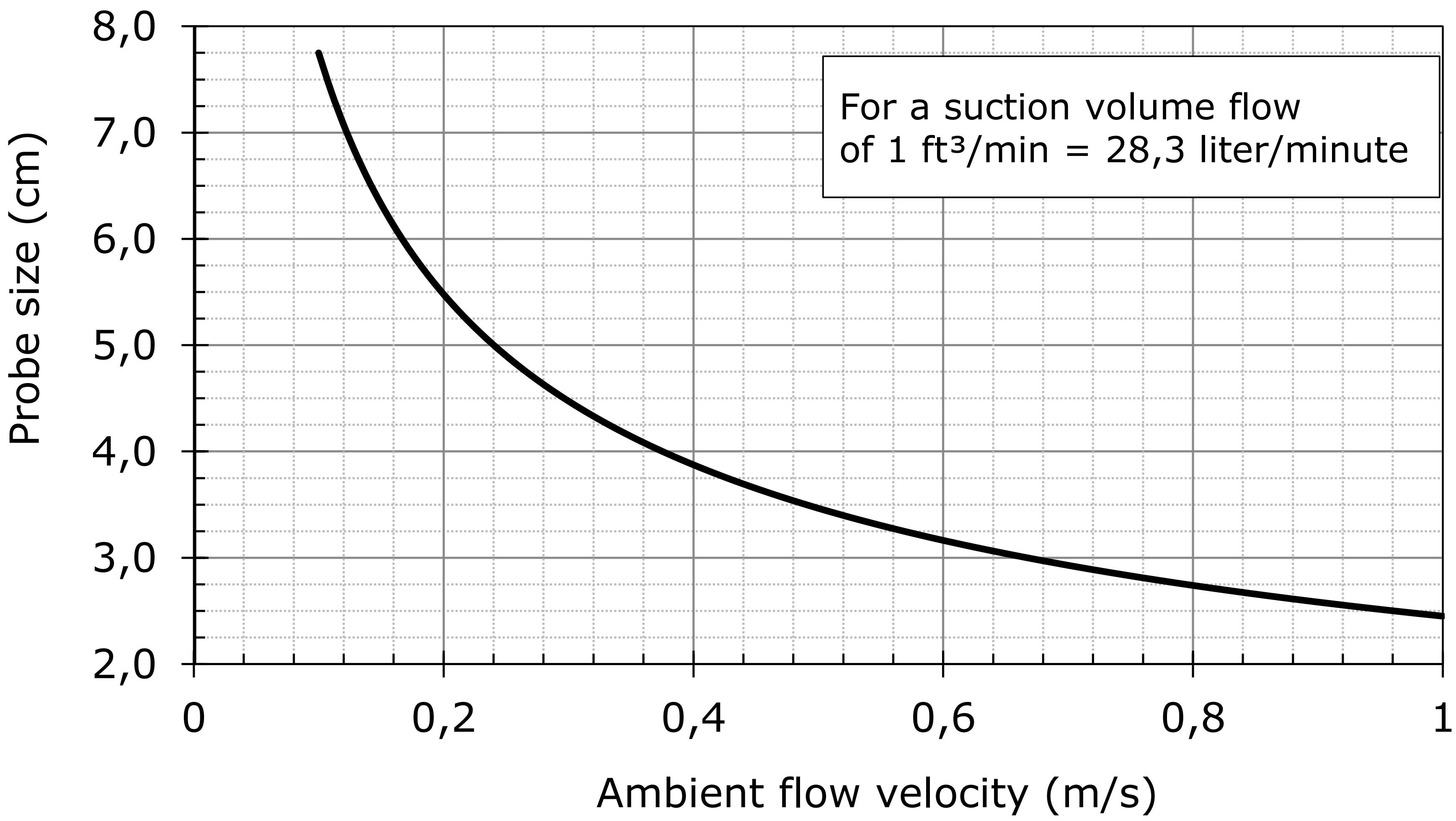
U ... inlet flow velocity

(Tränkler und Reindl 2014)

Inclined orientation



Isokinetic probe size



Sampling

- Isokinetic sampling not always feasible

- Sub-isokinetic:
  - Suction velocity is lower than the approach (free-stream) velocity
  - Large particles deviate from the streamlines and are more likely to enter the probe

- Super-isokinetic:
  - Suction velocity is higher than the approach velocity
  - Large particles deviate from the streamlines and are less likely to enter the probe

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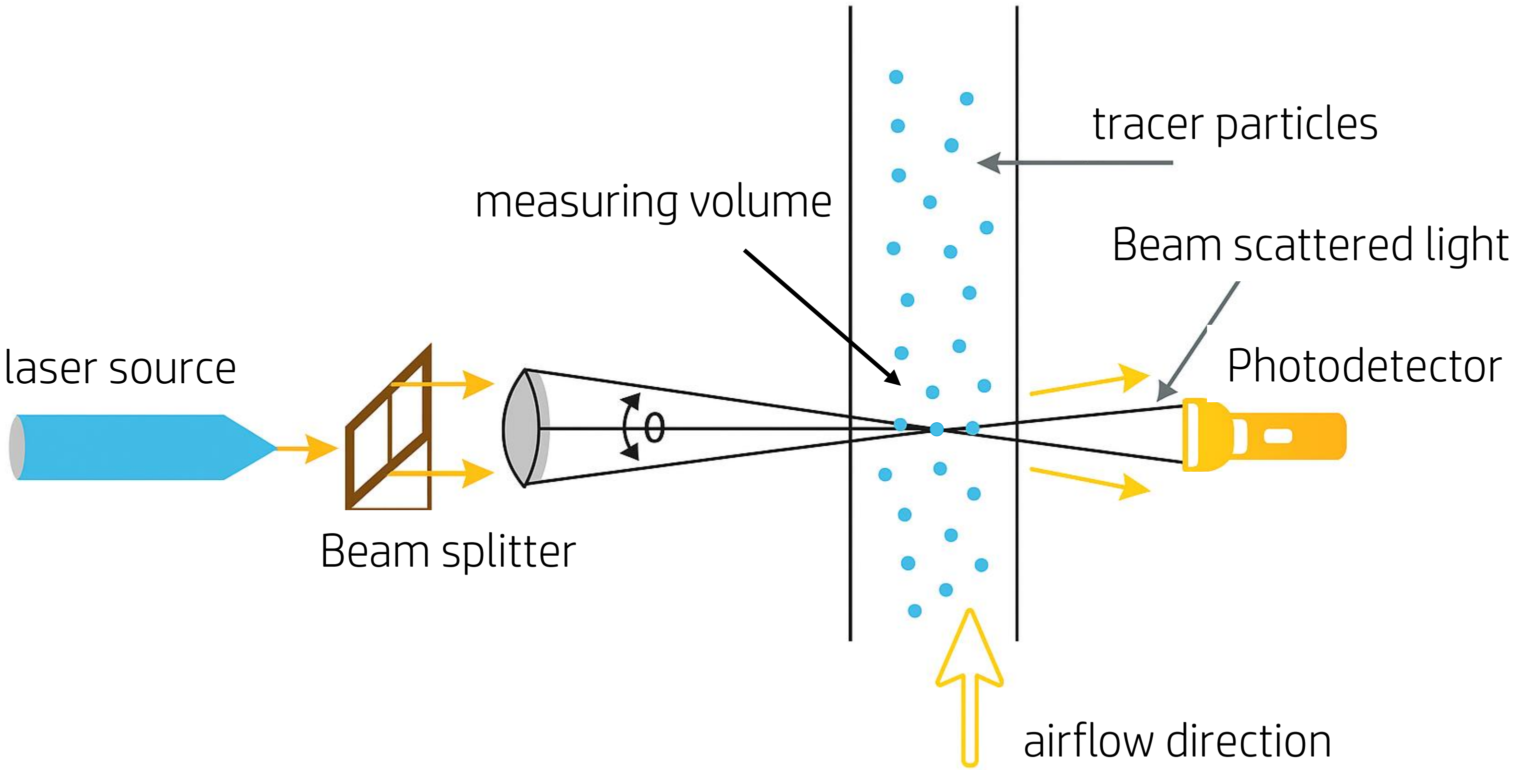
Laser Doppler Anemometry



(GoPhotonics, 2025)

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Laser Doppler Anemometry

- **Laser Source:** A laser beam is emitted by a light source (e.g., He-Ne laser, argon-ion laser).
- **Beam Splitter:** The laser beam is split into two coherent beams by a beam splitter.
- **Focusing and measurement volume:** The two beams are crossed at a certain angle and focused to a point where they intersect (measurement volume).
- **Interference fringe pattern:** At the intersection point (measurement volume), an interference fringe pattern of bright and dark stripes is created.
- **Tracer particles:** Small particles (tracers) carried by the fluid pass through the interference pattern.
- **Scattered Light Signal:** The particles scatter light, which is detected by a photodiode or photodetector.
- **Signal Processing:** The frequency of the scattered light signal is proportional to the velocity component of the particles perpendicular to the interference fringes. The signal is analyzed using fast Fourier transform (FFT) and converted into a velocity value.

Velocity measurements

Vane anemometer:

- measurement area depends on vane size
- + robustness, ease of handling
- – directional dependence, inertia

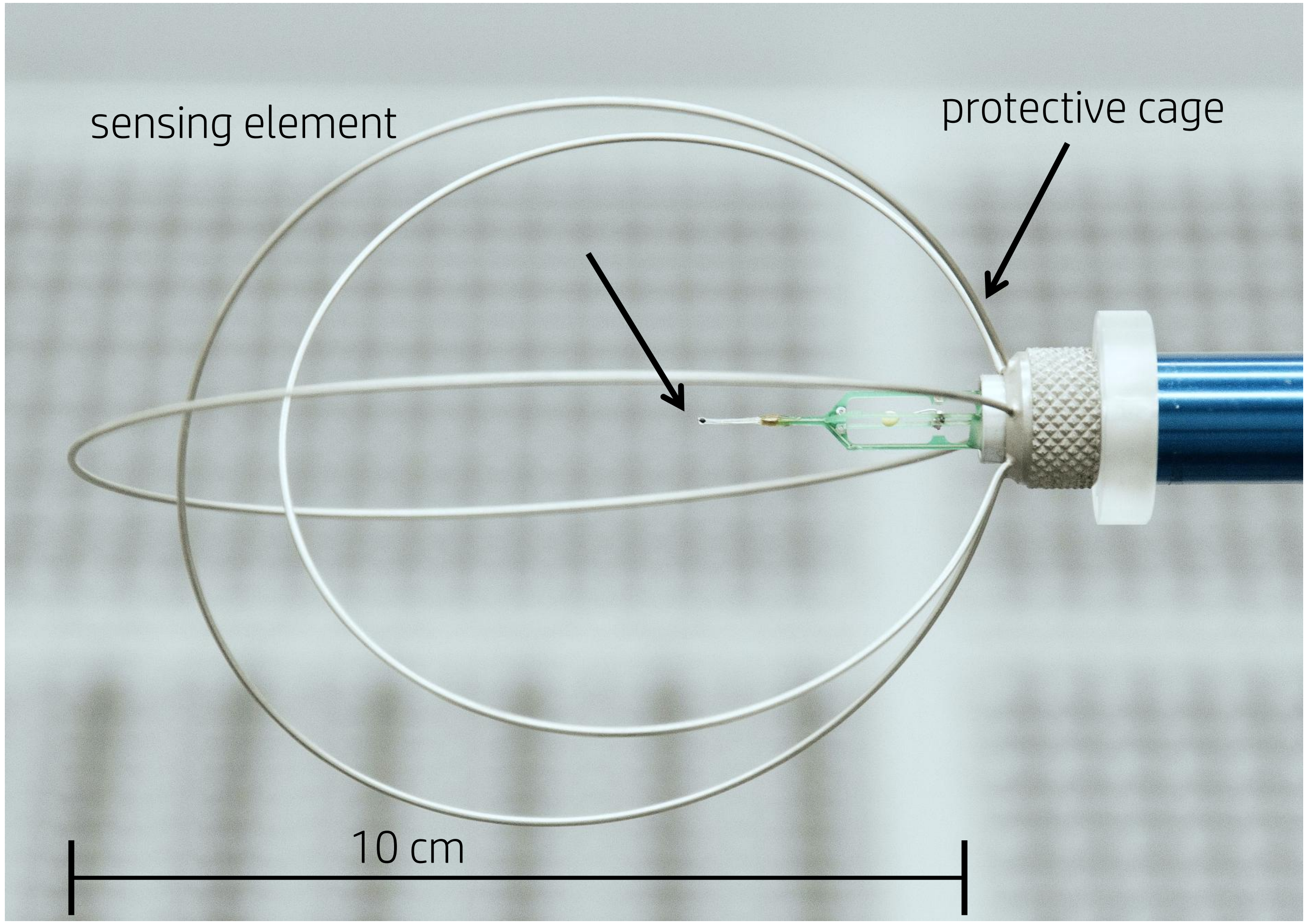
Hot-wire anemometer:

- nearly point-like measurement
- direction-independent / direction-dependent
- + fast response
- – sensitivity (fragile)

Vane and hot-wire anemometer
(Testo, 2021 & TSI, 2020)

Velocity measurements

Hot-wire anemometer



Hot wire anemometer

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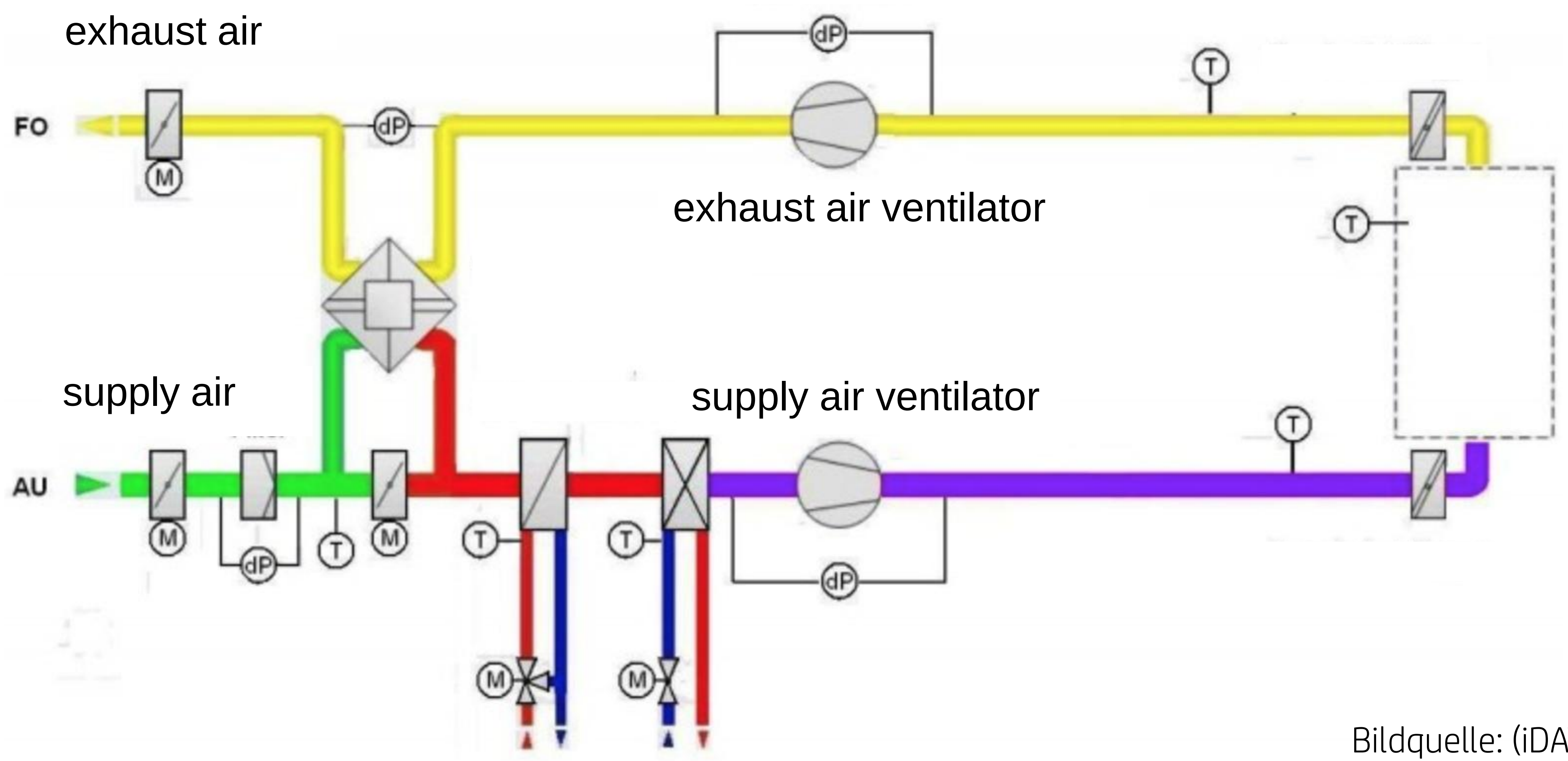
Volume Flows and Pressures



Bildquelle: (iDAT, 2023)

Volume flows and pressures

(TSI, 2020)

Flow capture hood

Volume flows and pressures

- measurement principle: grid-based velocity measurement at the bottom of the hood
- 16 measurement points (pressure probes, pitot tubes)
- evaluation using a micromanometer

$$q_V = C \cdot A \cdot \sqrt{\frac{2\Delta p}{\rho_1}}$$

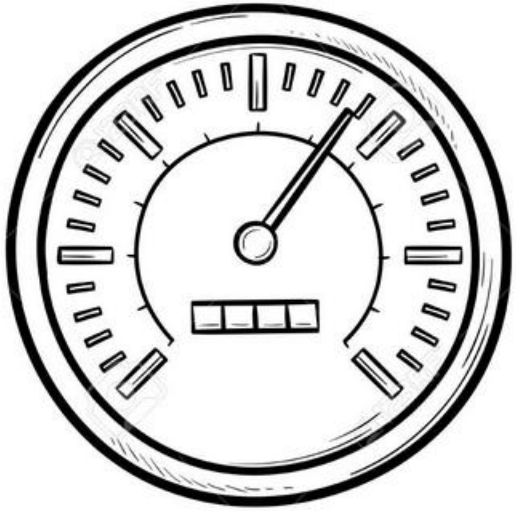
q_V… volumetric flow rate (m^3/s)
C… discharge coefficient, device-specific constant (-)
A… cross-sectional area (m^2)
Δp… differential pressure (Pa)
ρ_1… fluid density (kg/m^3)

Volume flows and pressures

Summary

Pressure cascade:

- Purpose: Monitoring & control of room pressure hierarchy
- Tool: differential pressure sensor



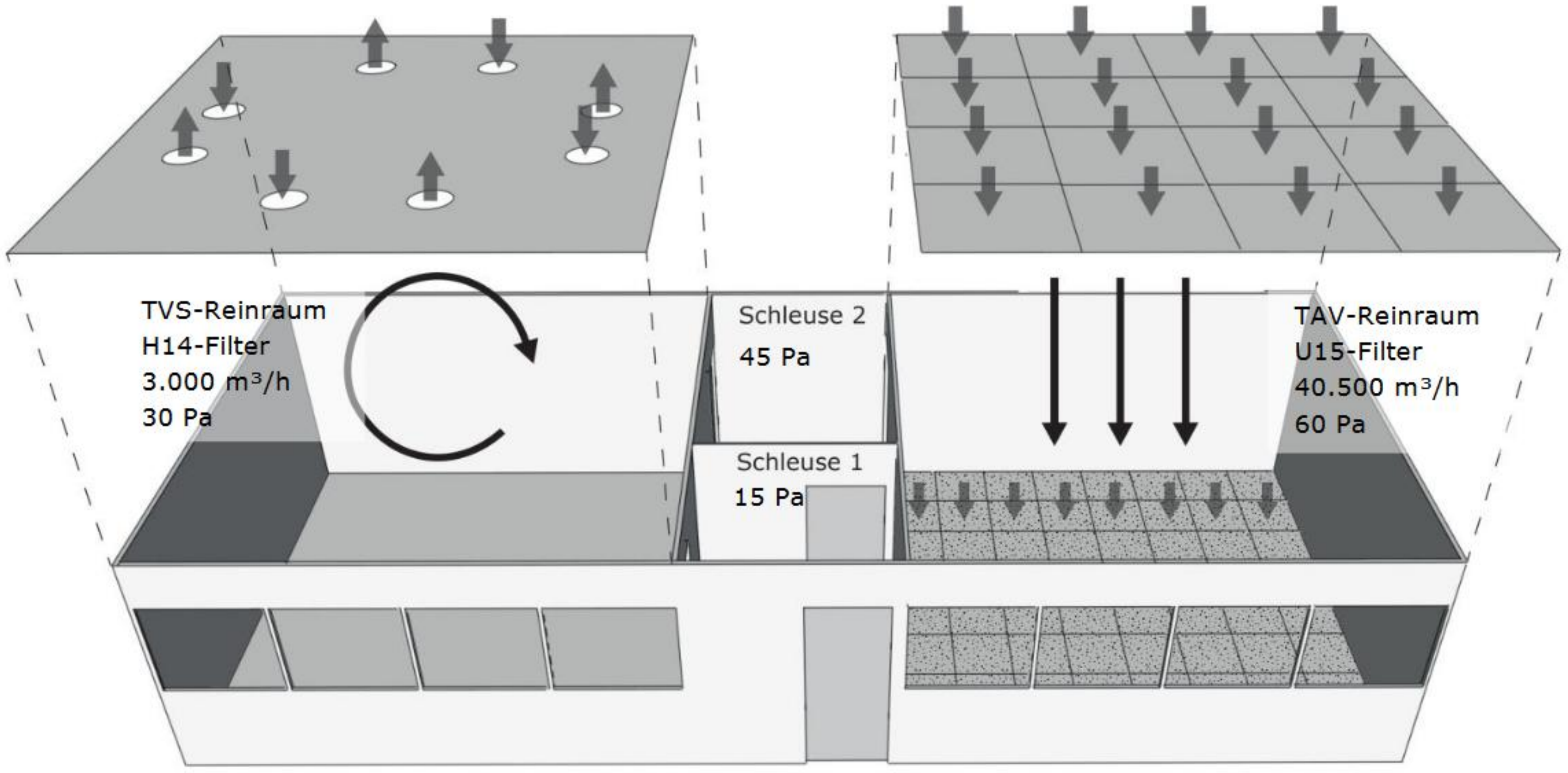
Airflow Measurement:

- Methods:
  - Pitot tubes / flow grids → dynamic pressure
  - Orifice plates → pressure drop

Sensor:

- Differential pressure sensor

Volume flows and pressures



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Turbulence intensity

Definition of Turbulence

- A chaotic and stochastic flow condition superimposed on the main flow direction.

Effects

- increased pressure loss
- enhanced diffusion of vector quantities (e.g., velocity, momentum, …)
- enhanced diffusion of scalar quantities (e.g., temperature, concentration, …)

(Schneider, 2012)

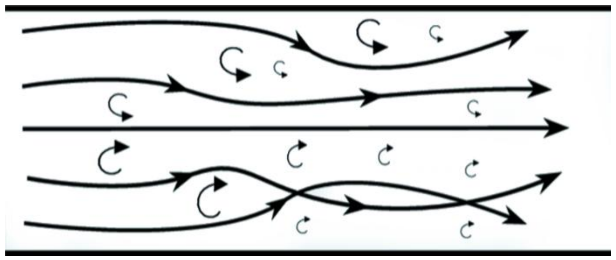
Turbulence intensity

Laminar flows

- undisturbed flow paths (streamlines)
- momentum exchange between adjacent fluid particles through molecular interactions

Turbulent flows

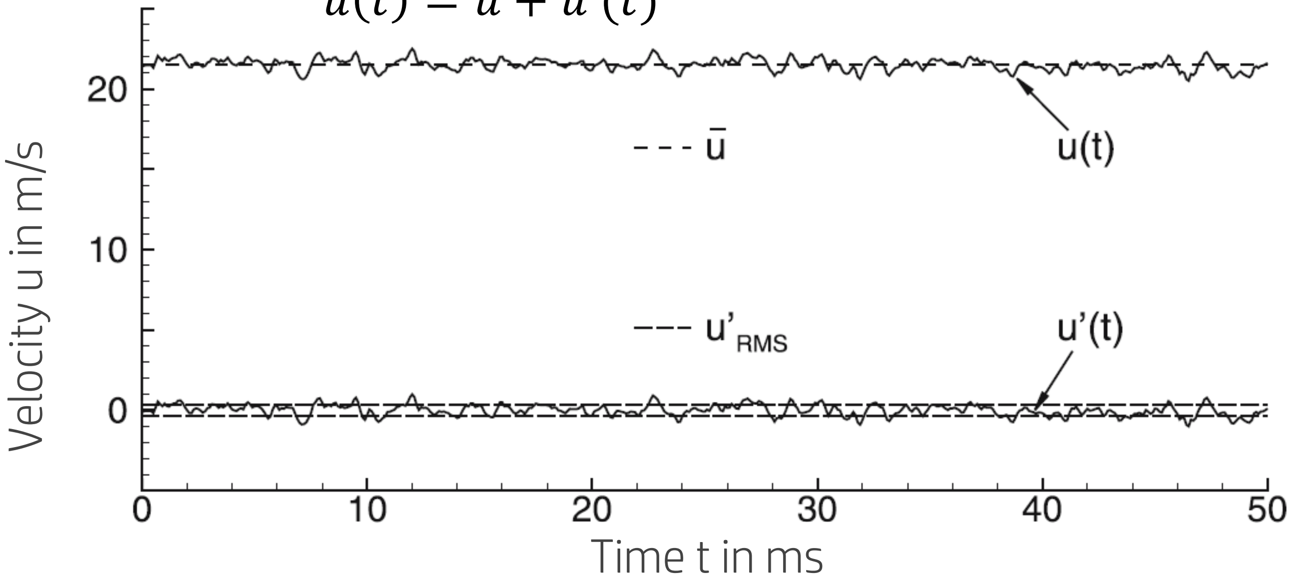
- strong fluctuations in flow velocity
- fluctuation components in all three spatial directions
- momentum exchange significantly increased due to turbulent fluctuations



thesensorsguide.com

Turbulence intensity

$$u(t) = \bar{u} + u'(t)$$



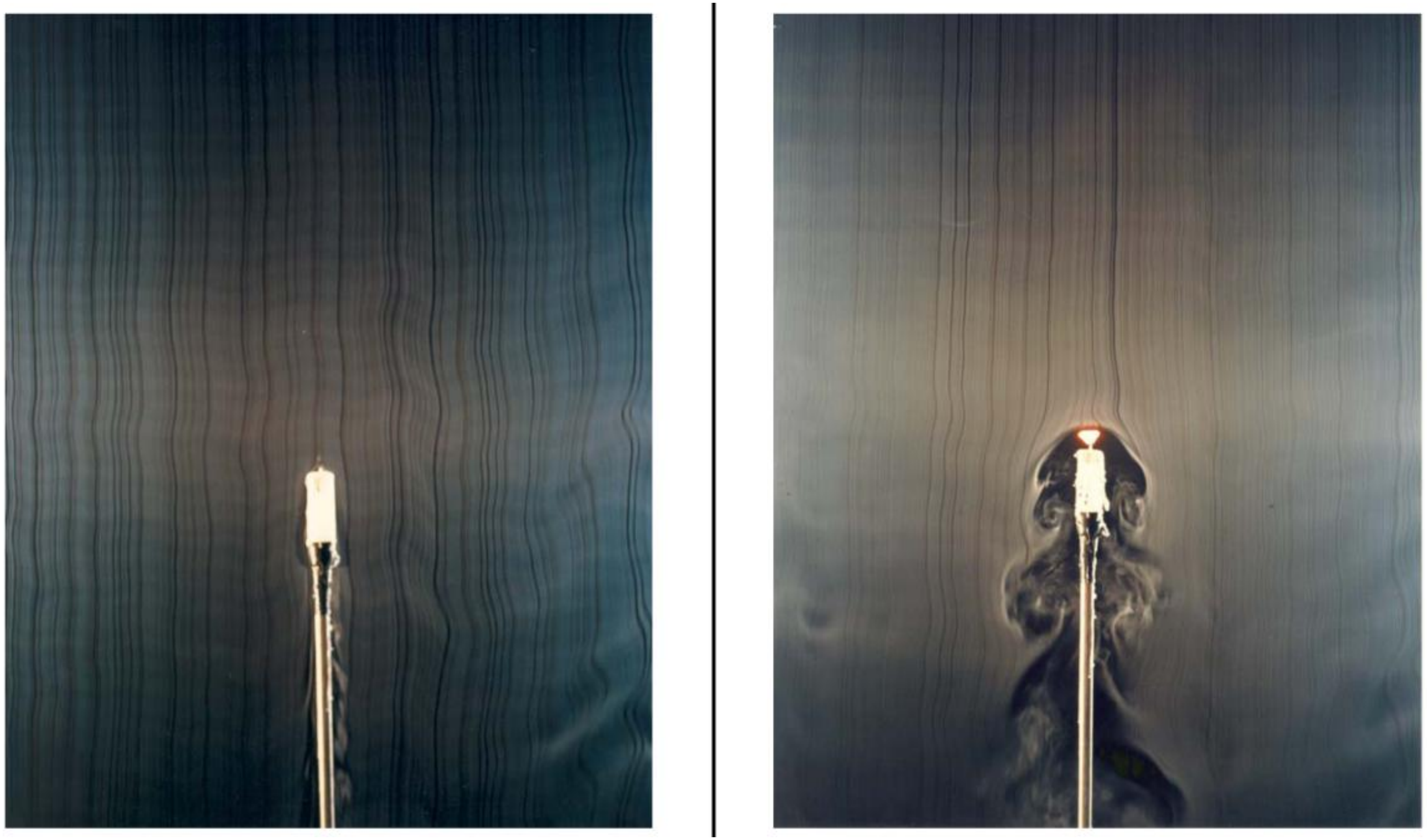
(Brunn 2006)

$$Tu = \frac{\sqrt{\overline{u'^2}}}{\bar{u}} = \frac{\sqrt{\frac{\sum_{i=1}^{n}(u_i - \bar{u})^2}{n-1}}}{\bar{u}}$$

$u(t)$	Instantaneous velocity
$u'(t)$	Fluctuation velocity
$\bar{u}$	Mean velocity
u'_{RMS}	(RMS) of the velocity fluctuations
t	Time
Tu	Turbulence intensity

Turbulence intensity

Impact of heat sources



(Fitzner 1992)

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Measurement uncertainty

- **error** vs. **uncertainty**
- Every measurement is inherently subject to:
  - a measurement **error** (classical error analysis according to Gauss), or
  - a measurement **uncertainty** (according to GUM – Guide to the Expression of Uncertainty in Measurement)
- A gross measurement error can occur due to:
  - improper use of the measuring instrument
  - a defective sensor or measuring device
  - an unsuitable measurement setup
  - human error in general
    → These must absolutely be avoided!

Measurement uncertainty

Measurement Uncertainty according to GUM

- State of the Art:
  The GUM – Guide to the Expression of Uncertainty in Measurement (GUM 1995)
  developed in the 1980s based on the recognition that classical Gaussian error analysis is incomplete.

Terminology:

- **measurement error:** an actual error in the sense of a mistake or blunder (e.g. due to misuse or defect)
- **measurement deviation:** the difference between the true value and the measured value

Measurement uncertainty

Measurement Uncertainty According to GUM

- Specification
  - best estimate (arithmetic mean)
  - associated measurement uncertainty
  - e.g. 34.25 °C ± 0.2 °C

- Two types of evaluation
  - **Type A:** calculated from repeated measurements *(only applicable to statistical data)*
  - **Type B:** based on documented information, e.g., calibration certificates for dynamic quantities

Thank you for your attention

Image source: photo from Alexas_Fotos on Unsplash.com

Sources

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(GoPhotonics, 2025)	LDA, https://www.gophotonics.com/community/what-is-laser-doppler-velocimetry (26.06.2025)

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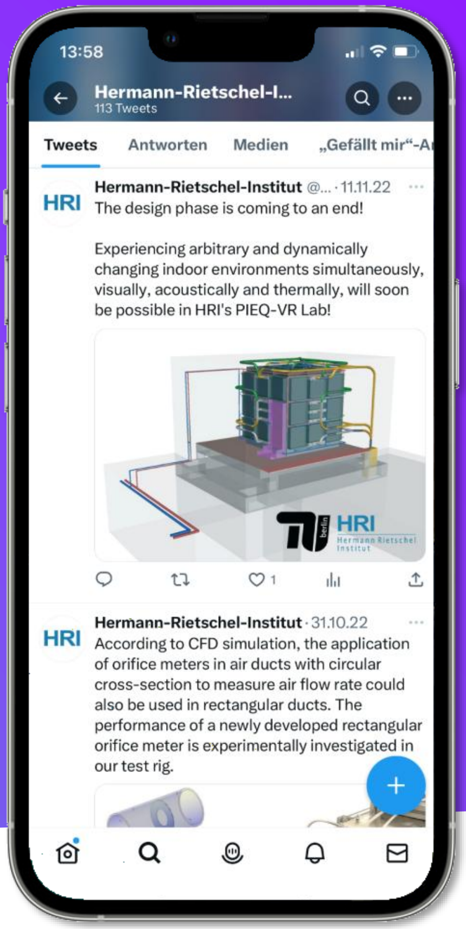

Julia Lange
Hermann-Rietschel-Institut, Technische Universität Berlin

Mail: julia.lange@tu-berlin.de
Website: hermann-rietschel-institut.de