Flow- (and H2-Concentration) Measurements at Pro-Science/KIT

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Pre-normative REsearch for Safe use of Liquid HYdrogen

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- DISCHA-Facility
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Overview

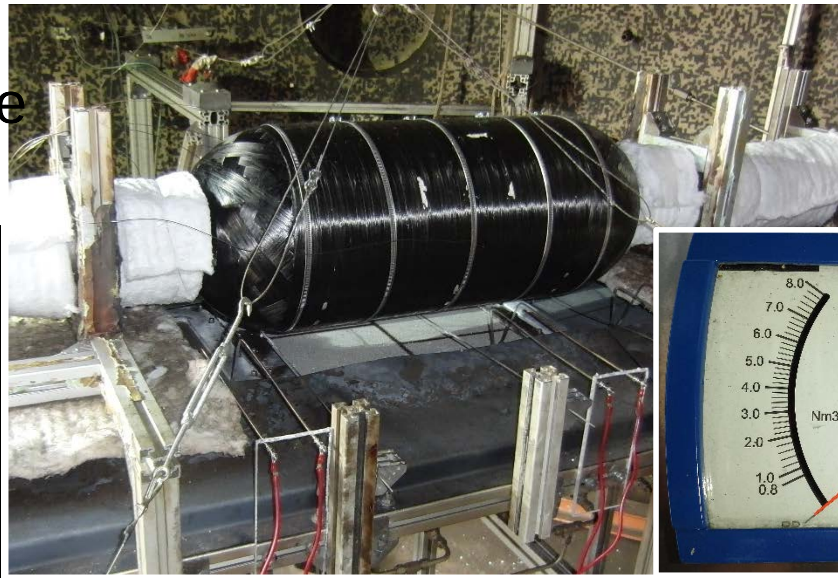
- Numerous flow sensors using several different measurement principles are available, the most common ones are:
  - Mechanic (float-type flow meter, rotameters, vane wheels)
  - Acoustic (ultrasonic sensors)
  - Thermal (thermal conductivity)
  - Pressure (Venturi, Pitot/Prandtl)
  - Magnetic
  - Coriolis

Mechanical flow sensors

- Float-type flow meters:
  - Principle:
    Flowing medium lifts up a conical weight,
    flow velocity is proportional to height.
  - Advantages:
    - relatively simple and cheap,
    - no external energy supply necessary,
    - display without electrical energy,
    - independent of electrical conductivity,
    - measurement of smallest gas and liquid flows,
    - high reproducibility.
  - Disadvantages:
    - limited accuracy,
    - no flow fields,
    - calibration necessary for every fluid,
    - with changing medium properties scale has to be converted,
    - only applicable in vertical orientation (upward flow).

Mechanical flow sensors

- Applications at KIT/PS:
  - KROHNE float-type flow meters
    (several devices available, typical specifications):
    - Measuring range: < 50 Nm³/h (13.9 l/s)
    - Temperature range: -20...+100°C
    - Pressure Range: < 10 bar
    - Accuracy: ± 1.0%
  - Smaller devices used for flow control of pumps for Messkonzept H2-sensors.
  - Larger ones used for air/fuel control of pre-mixed air/methane burner for bonfire tests under inertized atmosphere.



Mechanical flow sensors

- Vane wheel probes
  - Principle:
    Flowing medium drives propeller, rotation velocity is proportional to flow velocity.
  - Advantages:
    - relatively simple and cheap,
    - easy and fast application
    - wide range of diameters and geometries
    - very sensitive to flow direction
  - Disadvantages:
    - Intrusive,
    - very sensitive to flow direction,
    - limited accuracy,
    - very sensitive to medium (mostly clean gases),
    - very sensitive to particles,
    - vulnerable to abrasion,
    - limited temperature range (mostly positive °C).

Mechanical flow sensors

- Vane wheel probes (similar: rotameters)
  - Principle:
    Installed into pipe where flowing medium drives propeller, rotation velocity is proportional to flow velocity.
  - Advantages:
    - Simple principle ➔ cheap,
    - Rather easy and fast application,
    - Wide range of diameters and geometries,
    - Not sensitive to flow direction,
    - Higher accuracy.
  - Disadvantages:
    - Intrusive,
    - Very sensitive to medium (mostly clean gases),
    - Very sensitive to particles,
    - Vulnerable to abrasion,
    - Limited temperature range (mostly positive °C).

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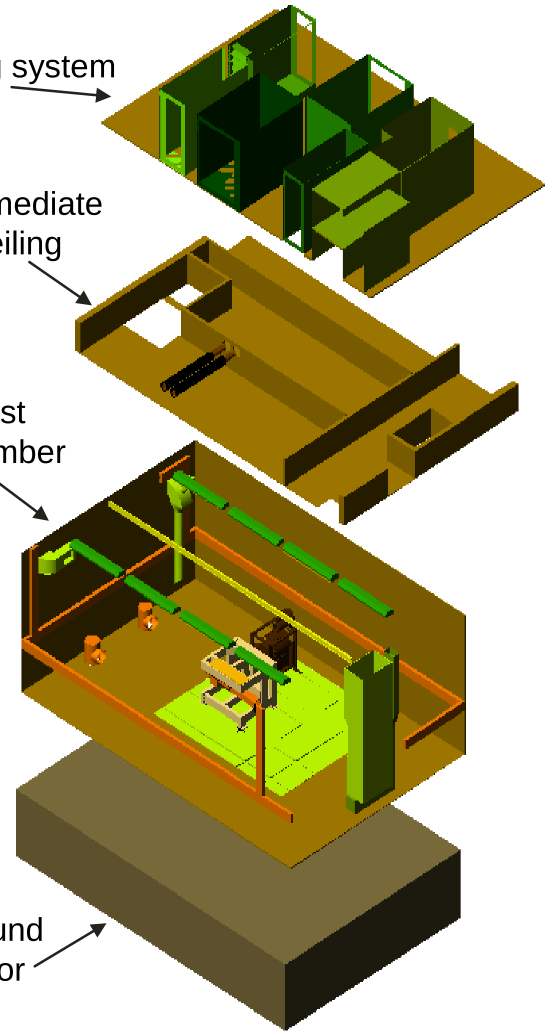
Mechanical flow sensors

- Applications at KIT/PS:
  - Vane wheel Testo 416:
    - Measuring range: + 0.6 ... + 40 m/s
    - Temperature range: 0 ... + 60 °C
    - Accuracy: ± (0.2 m/s + 1.5% MV)
    - Resolution: 0.1 m/s
    - Dimensions: 182 × 64 × 40 mm

Mainly used for rough estimations of a flow field, e.g. to analyze details the flow field in the test chamber with different settings of the venting system.

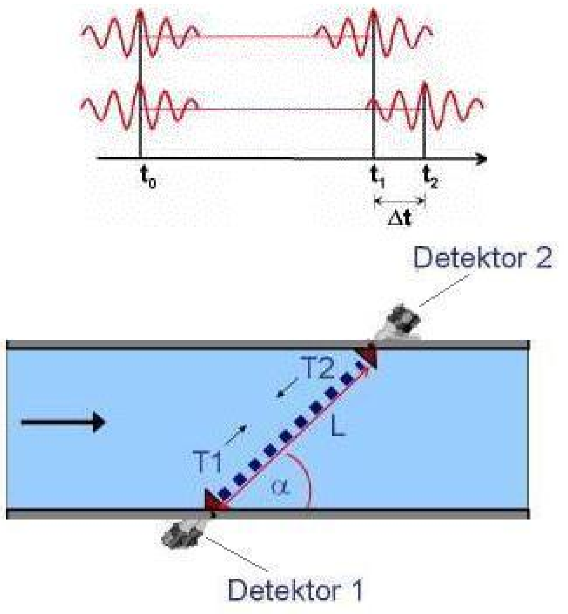
Test-Chamber

l = 8.5 m; b = 5.5 m;
h = 3.4 m; V = 160 m³



Ultrasonic flow sensors

- Principle:
  - **Transmission flow meters**
    Difference between transit time of ultrasonic pulses propagating with and against the flow direction is measured. Time difference is a measure for the average velocity of the fluid along the path of the ultrasonic beam. Apart from averaged fluid velocity the speed of sound can be calculated using the absolute transit times t_{up} and t_{down}.
    In-line (intrusive) or clamp-on (non-intrusive) devices available.



  - **Doppler shift flow meters**
    Doppler shift results from reflection of ultrasonic beam off sonically reflective materials (solid particles or entrained air bubbles) in a flowing fluid (or the turbulence of the fluid). Application: slurries, liquids with bubbles, gases with sound-reflecting particles.
  - **Open channel flow meters**
    Ultrasonic element is actually measuring height of water in the open channel; based on the geometry of the channel, the flow can be determined from the height. The sensor usually also has a temperature sensor since speed of sound in air is affected by temperature.

Ultrasonic flow sensors

- Advantages:
  - Mostly cheap and easy to maintain (no moving parts),
  - Precise measurements over wide areas are possible,
  - Insensitive to pressure and flow-peaks, vibrations, (few) particles in the flow,
  - High-temperature models for temperatures up to 500 °C available,
  - suitable for use in legal metrology.

- Disadvantages:
  - Limited temperature range (mostly positive °C),
  - Extremely high viscosity dampens propagation of sound waves, therefore there are limits for the viscosity (only plays a role in a very small number of individual cases),
  - High gas contents lead to an increased compressibility of the medium and to an extremely low sound velocity.
  - Not all media can be measured:
  - Bubbles ➔ reflections / damping ➔ max.: 1 Vol.-%
  - Solid particles ➔ reflections ➔ guide value: < 5 Vol.-%
  - Viscosity ➔ damping ➔ guide value: max. 0.1 kg/(m·s) / d_i [m]

Ultrasonic flow sensors

- Available at KIT/PS: Ultrasonic Anemometer Young 81000
  - Measuring range: 0 to 40 m/s (0 to 90 mph)
  - Resolution: 0.01 m/s
  - Accuracy: ±1% ±0.05m/s (30 m/s), ±3% (40 m/s)
  - Wind Direction: 0 to 360 degrees
  - Elevation Range: ±60 degrees
  - Resolution: 0.1 degree
  - Accuracy: ± 2 degrees (30 m/s), ± 5 degrees (40 m/s)
  - Speed of Sound: 300 to 360 m/s
  - Resolution: 0.01 m/s
  - Accuracy: ± 0.1% ± 0.05 m/s (30 m/s)
  - Sonic Temperature: -50 to +50°C
  - Resolution: 0.01 m/s
  - Accuracy: ±2°C (30 m/s)
  - Operating Temperature: -50 to +50°C
  - Dimensions: 56cm high x 17cm radius (3 support arms)
  - Weight: 1.2 kg (2.6 lb)

Ultrasonic flow sensors

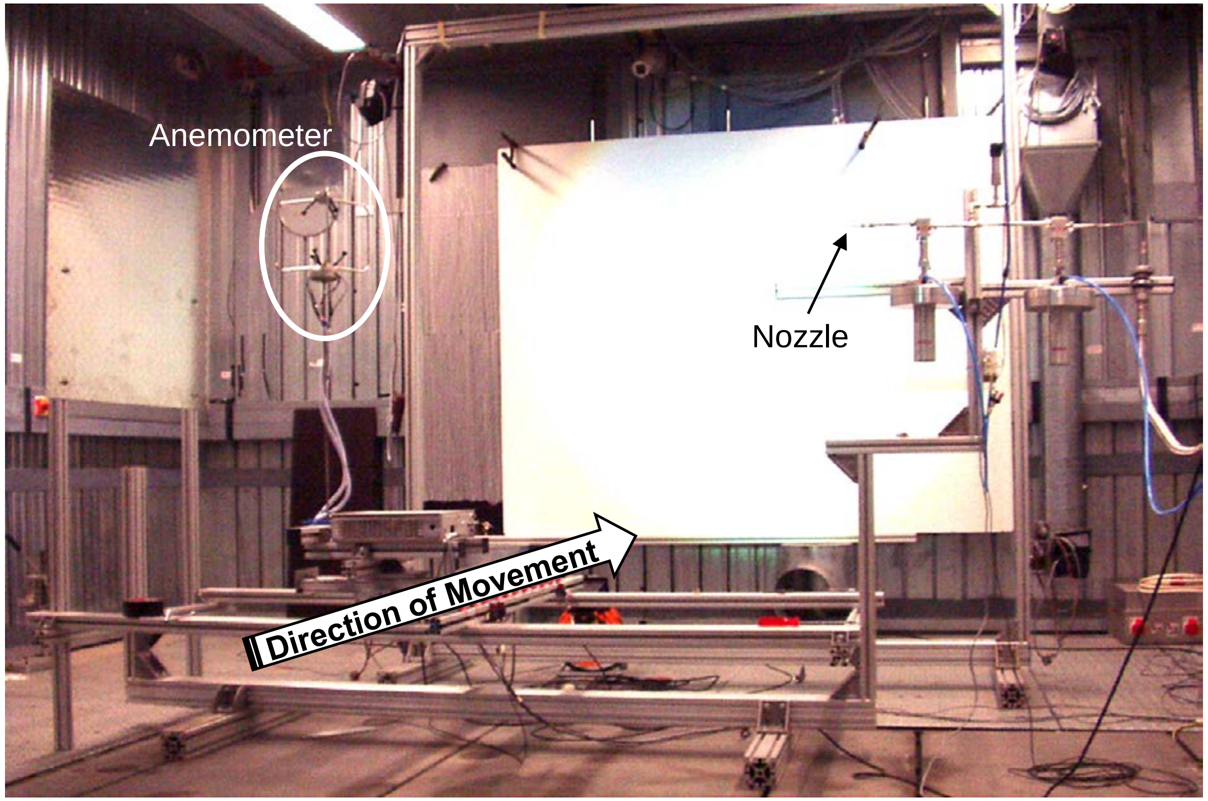
- Applications at KIT/PS: Ultrasonic Anemometer Young 81000
  - Used as anemometer to analyze flows around objects, e.g. in the test chamber Q160,

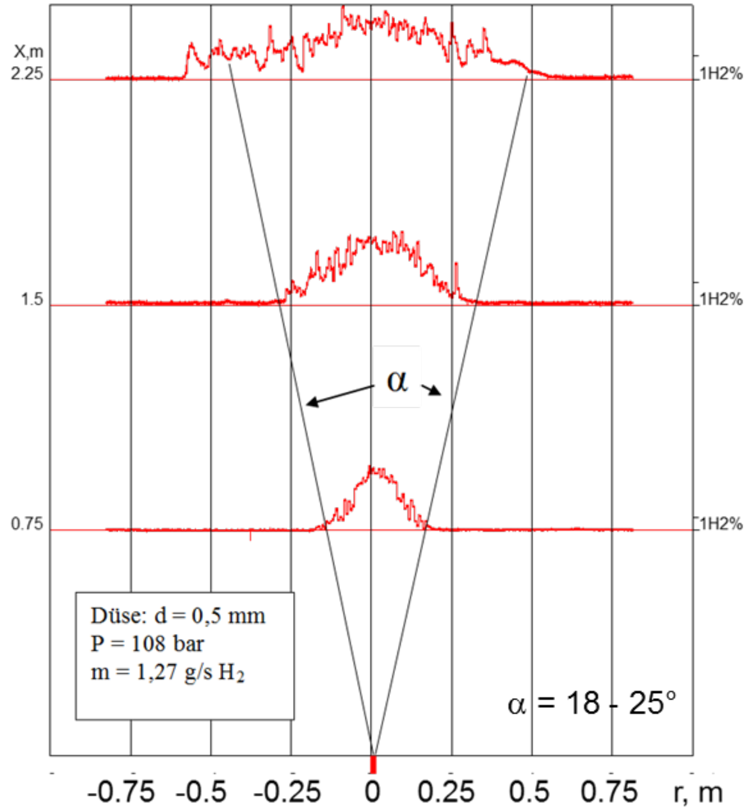
  But also: Utilization of Young 81000 as H2-Sensor

  - Speed-of-sound is proportional to H2-concentration
  - Speed-of-sound is one of the output-signals and can be easily recorded:
    VOLTAGE OUTPUT (4 CHANNELS)
    - Range: 0 to 4 V
    - Resolution: 12 Bit
    - Accuracy: ± 0.1% of full scale
    - Frequency: 4 to 32 Hz (selectable)
  - Limiting factor is measuring range for speed-of-sound (300 to 360 m/s), outside this range either 0 or 4 V is displayed,
  - H2-concentration limits were approx. 15 Vol% (@ T_{amb} ≈ 4 °C) and 10 Vol% (@ T_{amb} ≈ 20 °C)

Ultrasonic flow sensors

- **Utilization of Young 81000 as H2-Sensor**
  Sensor mounted on automated sledge and driven through H2-jet.

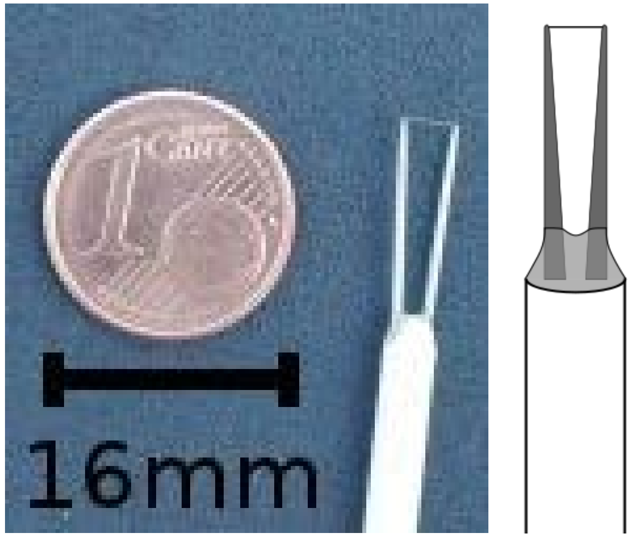




- Fast and accurate measurement of concentration profiles in a jet,
- But only applicable in limited H2-concentrations
  (approx. 15 Vol% (@ T_{amb} ≈ 4 °C) and 10 Vol% (@ T_{amb} ≈ 20 °C))

Thermal flow sensors

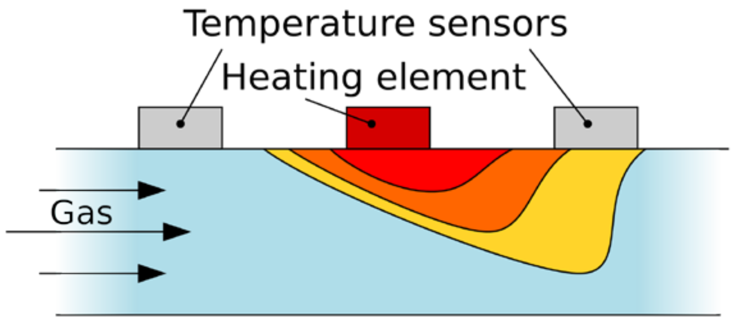
- Hot wire anemometer
  - Passing air cools an electrically heated fine wire (e.g. tungsten, thickness in order of micrometers). Resistance of wire is dependent upon temperature, so resistance of wire is proportional to flow speed. Different circuits are used that try to keep one of the variables (current, voltage or temperature) constant, so several realizations exist (CCA, CVA & CTA: “constant [variable] anemometer”).



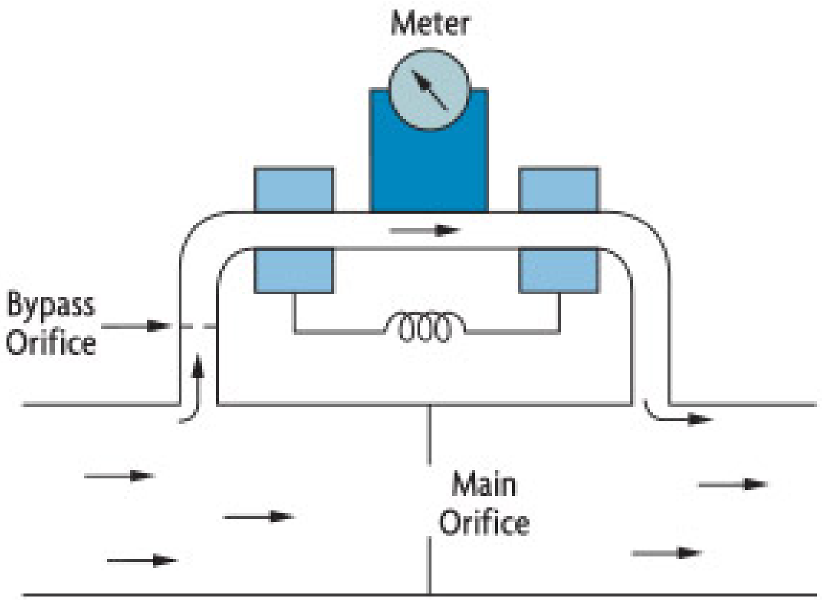
  - Advantages:
    - extremely high frequency-response,
    - fine spatial resolution
    - almost universally employed for the detailed study of turbulent flows, or any flow in which rapid velocity fluctuations are of interest.
  - Disadvantages:
    - extremely delicate
    - no particles in flow,
    - Sensitive to temperature changes.

Thermal flow sensors

- Thermal dispersion flow meter:
  heat is transferred to the boundary layer of the fluid flowing over a heated surface. Commonly used for general industrial gas flow applications in pipes and ducts.



- Capillary-tube flow meter:
  heat is transferred to the bulk of the fluid flowing through a small heated capillary tube.
  Primarily used for smaller flows of clean gases or liquids in tubes. This type is most widely used for thermal mass flow meters in industry.

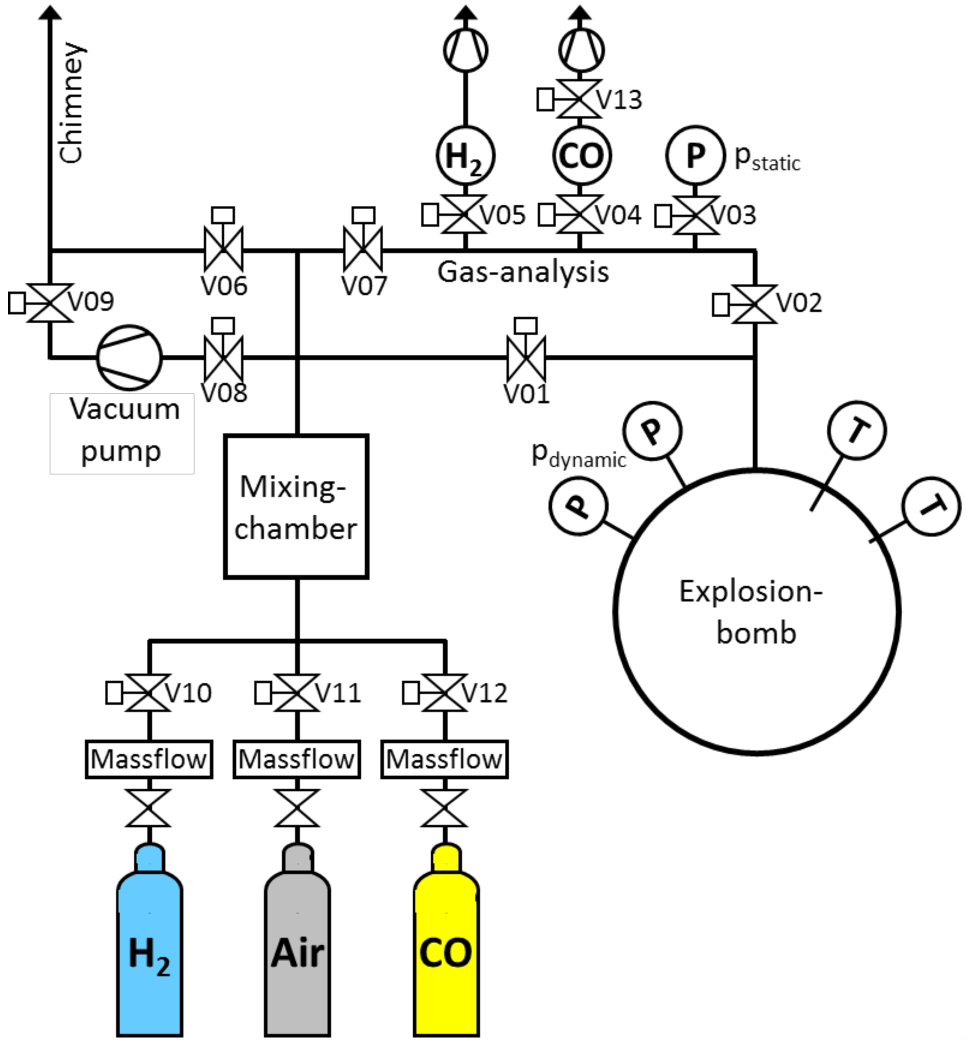


Thermal flow sensors

- Available at KIT/PS: Bronkhorst El-Flow (capillary-tube flow meters)
  - Accuracy (incl. linearity): standard: ±0,5% Rd plus ±0,1%FS
    (based on actual calibration) ±0,8% Rd plus ±0,2% FS for F-110C-005/F-200CV-005
    ±2% FS for F-110C-002/F-200CV-002
  - Turndown: 1 : 50 (in digital mode up to 1:187,5)
  - Repeatability: < 0,2% Rd
  - Settling time (controller): standard: 1...2 seconds
    option: down to 500 msec
  - Control stability: < ±0,1% FS (typical for 1 ln/min N2)
  - Operating temperature: -10...+70°C
  - Temperature sensitivity: zero: < 0,05% FS/°C;
    span: < 0,05% Rd/°C
  - Pressure sensitivity: 0,1% Rd/bar typical N2;
    0,01% Rd/bar typical H2
  - Leak integrity, outboard: tested < 2 x 10-9 mbar l/s He
  - Attitude sensitivity: max. error at 90° off horizontal 0,2% at 1 bar, typical N2
  - Warm-up time: 30 min. for optimum accuracy
    2 min. for accuracy ± 2% FS

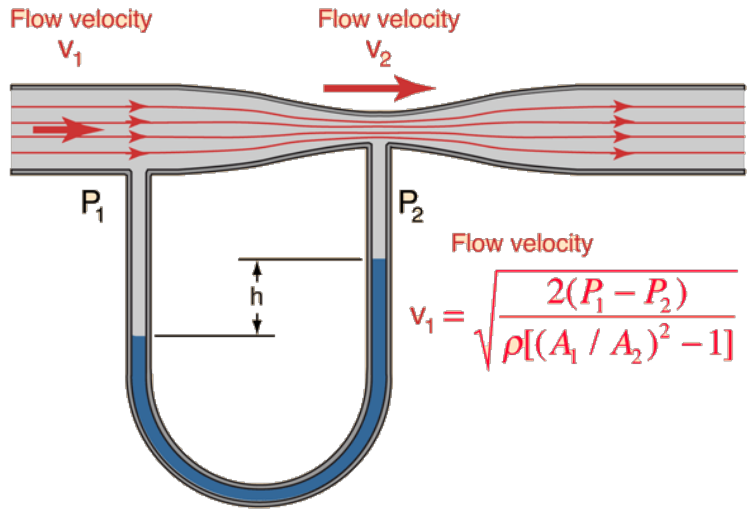
Thermal flow sensors

- Applications at KIT/PS:
  Used for mixture preparation in small and large geometries,
  - High accuracy allows simultaneous filling through a mixing chamber with several devices (e.g. for explosion bomb experiments with H2-CO-air-mixtures),
  - One device can be used for most gases, calibration factor is needed (provided by manufacturer for commonly used gases).

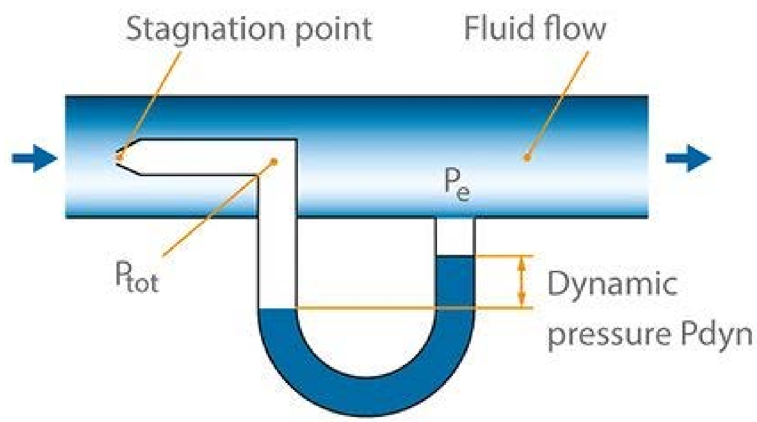


Pressure Flow sensors

- Venturi Meter:
  An incompressible fluid's velocity must increase as it passes through a constriction (principle of mass continuity), while its static pressure must decrease in accord with the principle of conservation of mechanical energy.
  By measuring the change in pressure, the flow rate can be determined.

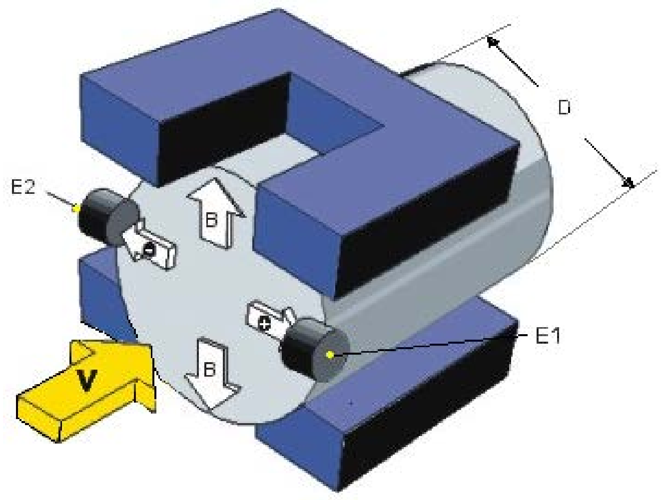


- Pitot static tube (Prandtl probe):
  Stagnation pressure and static pressure in the flow are measured. Difference Δp is the dynamic pressure, which is proportional to the flow velocity.



Magnetic flow meter

- Magnetic-inductive flow meter:
  measures fluid flow by the voltage induced across the liquid by its flow through a magnetic field.
  - A magnetic field is applied to metering tube, which results in a potential difference proportional to the flow velocity perpendicular to the flux lines due to electromagnetic induction.
  - Requires a conducting fluid, and an electrical insulating pipe surface, for example, a rubber-lined steel tube.
  - If the magnetic field direction were constant, electrochemical and other effects at the electrodes would make the potential difference difficult to distinguish from the fluid flow induced potential difference.
  - The magnetic field is constantly reversed in modern magnetic flowmeters to cancel out the electrochemical potential difference, which does not change direction with the magnetic field. So no permanent magnets can be used for magnetic flowmeters.

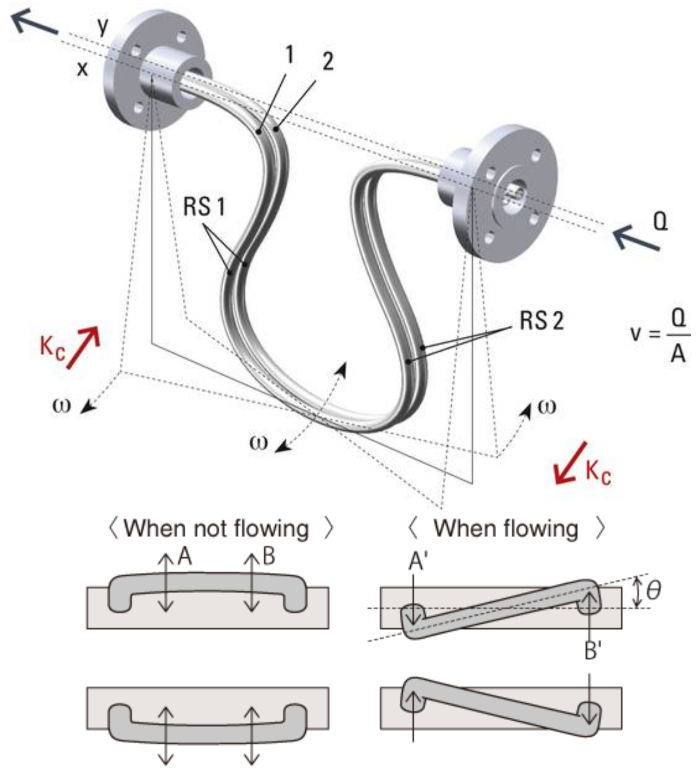


$$U_E = k \cdot B \cdot D \cdot v$$

U = voltage
B = magnetic field
D = tube diameter
v = flow velocity
k = proportionality factor

Coriolis Flow Meter

- Principle:
  - A vibration is induced on the bended tube through which the fluid passes (vibration is not completely circular, but provides the rotating reference frame that induces the Coriolis effect).
  - When no fluid is flowing, the motion of the two tubes is symmetrical,
  - During mass flow some twisting of tubes is observed:
    - Arm carrying flow away from rotation axis must exert a force on fluid to accelerate flowing mass to vibrating speed of tubes at the outside (increase of absolute angular momentum) ➔ lagging behind overall vibration.
    - Arm through which fluid is pushed back towards rotation axis must exert a force on fluid to decrease fluid's absolute angular speed (angular momentum) again ➔ this arm leads overall vibration.
  - Sensors monitor and analyze changes in frequency, phase shift, and amplitude of vibrating flow tubes.
  - Specific methods vary according to the design of the flow meter,
  - The changes observed represent mass flow rate and density of the fluid.



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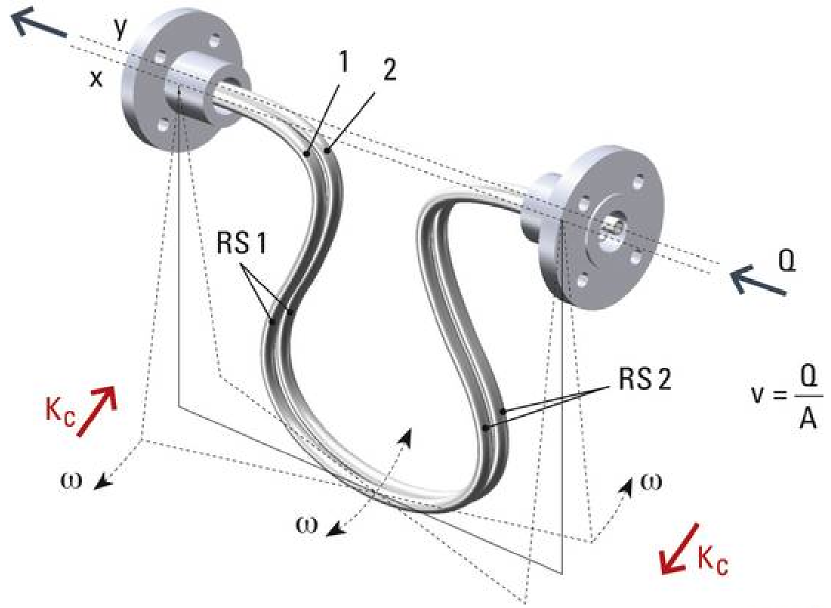
Coriolis Flow Meter

- Advantages:
  - Universal measurement system for mass, density and temperature, independent of
    - conductivity
    - entry and exit regions
    - flow profile
    - density of medium
      (and thus pressure and temperature)
  - Direct mass flow measurement
  - Very high accuracy (typically ± 0,15 % of measured Value, special Sensors up to ± 0,05 % of measured Value)
  - Multivariable measurement principle, simultaneous measurement of
    - Mass flow
    - Density
    - Temperature
  - No moving parts (maximum tube amplitude 30 µm ➔ „no movement")
  - Only one apparatus.

Coriolis Flow Meter

- Disadvantages:
  - Relatively expensive,
  - Limited applicability in multiphase media or media with high gas content,
  - Sediments might lead to errors, especially in density measurements,
  - Limited choice of material which comes in contact with medium (corrosion)
  - Medium has to be homogeneous.

- Applicability concerning LH2:
  - Some commercially available devices are rated down to 80 K, but none rated to 30 K,
  - Rather large mass that has to be cooled to LH2-temperature,
  - Tube material properties at 30 K.

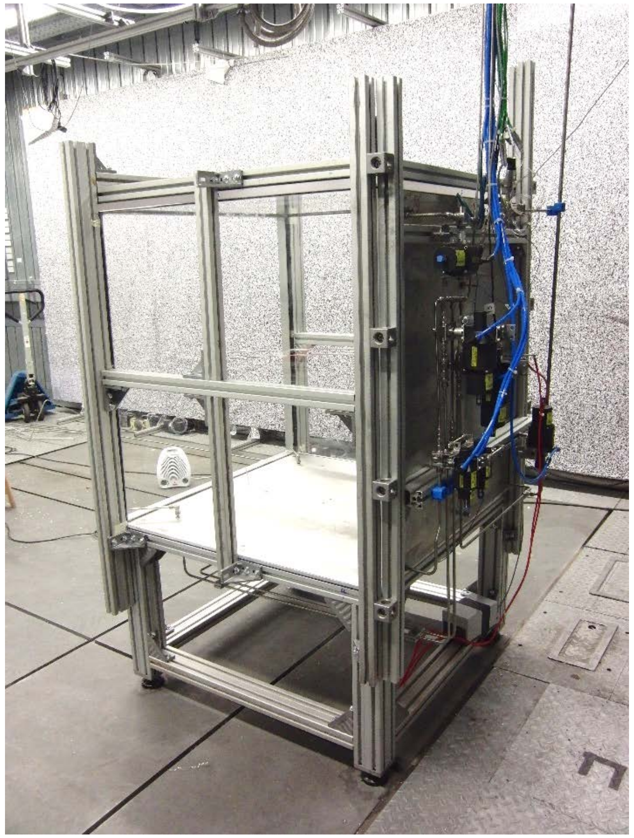


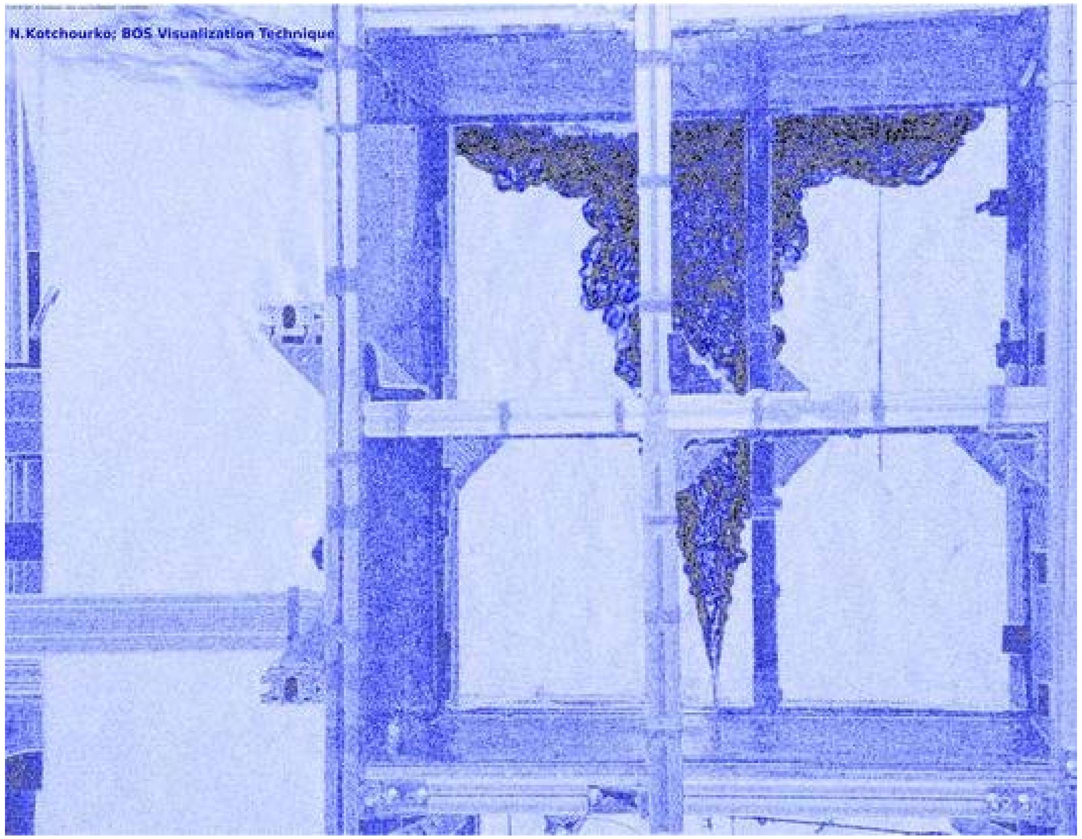
Coriolis Flow Meter

- Available at KIT/PS: Micro motion ELITE CMF010P325:
  - Accuracy (incl. linearity): 0.10% (Mass flow rate)
0.0005g/cm³ (Density)
±1 °C ±0.5% of reading (Temperature)
  - Repeatability: ±0.05% (Mass flow rate)
±0.0002 g/cm³ (Density)
±0.2 °C (Temperature)
  - Nominal / maximum flow rate: 70.2 l/h / 108 l/h (liquid)
  - Gas flow rates: 34 kg/h (mass) / 48 Nm³/h (volume)
  - Zero stability value: 0.004 kg/h
  - Maximum operating pressure: 414 bar(g)
  - Operating temperature: -50...+204°C
  - Temperature sensitivity: zero: < 0,05% FS/°C;
span: < 0,05% Rd/°C
  - Pressure sensitivity: 0,1% Rd/bar typical N2;
0,01% Rd/b

Coriolis Flow Meter

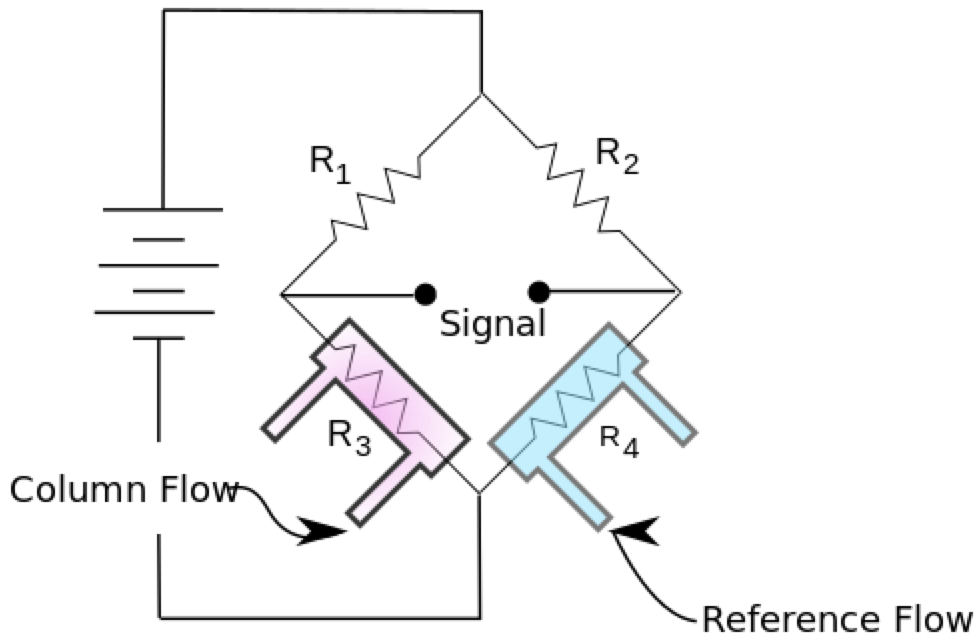
- Applications at KIT/PS:
  Used for release experiments with defined flow rates, e.g. HyIndoor WP4:
  - Defined H2-flows were injected into box (1 x 1 x 1 m³) with different vent-openings,
  - Jet was ignited to investigate burning/quenching behavior.





Messkonzept H2-sensors

- Principle: Thermal conductivity detector (TCD), "Katharometer"
  - The TCD consists of an electrically heated filament in a temperature-controlled cell. Under normal conditions there is a stable heat flow from the filament to the detector body. When the thermal conductivity of the gas changes, the filament also changes temperature and thus resistance.
  - The resistance change is often sensed by a Wheatstone bridge circuit with a reference flow over a second resistor in the four-resistor circuit for temperature compensation.



Messkonzept H2-sensors

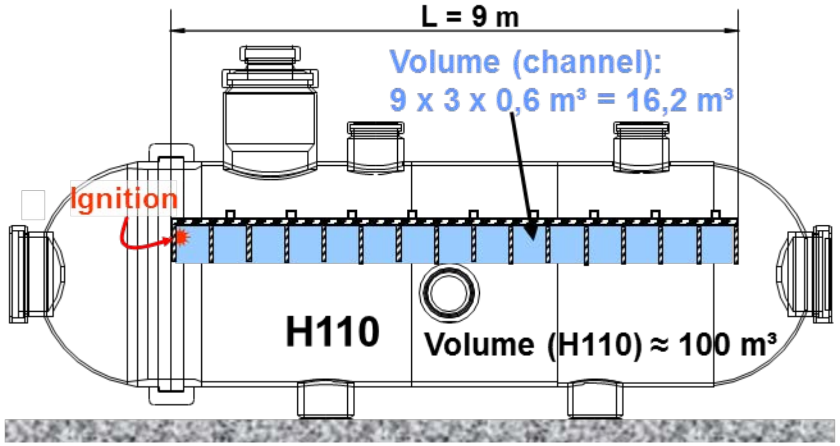
- Available at KIT/PS: FTC-300:
  - Measuring range: 0 – 100 Vol% H2 in N2 or air (other diluents on demand)
  - Linearity: < 1% of range
  - Warm up time: approx. 20 min (up to 1 h for small ranges)
  - Flow rate: 10 l/h-150 l/h (recommended 60 l/h to 80 l/h)
  - T90-time: <1 sec at flow rate higher 60 l/h (or user selected)
  - Noise: < 1% of smallest range
  - Repeatability: < 1% of range
  - Error due to change of ambient temperature: < 1% of smallest range per 10 °C
  - Error due to change of flow at 80l/h: < 1% of smallest range per 10 l/h
  - Gas pressure: Max. 2000 kPa (20 bar)
  - Error due to change of pressure (>800 hPa): < 1% of smallest range per 10 hPa

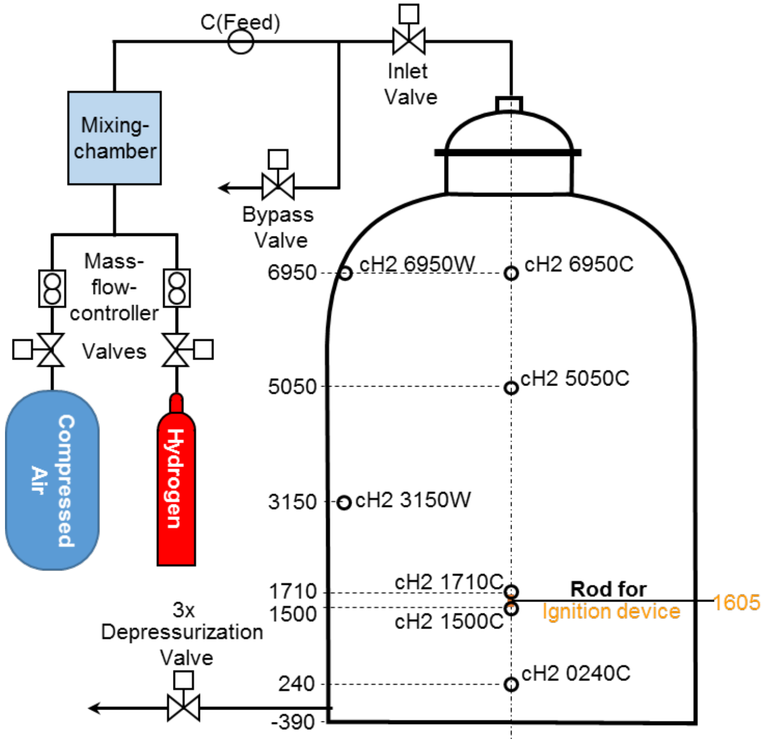
BUT:
- Measuring cell has to be protected by glass pearls for combustible gases,
- Measuring cell sensitive to high humidity, protective coating available,
- Measuring cell has to be kept at 60 °C ➔ temperature limit.

Messkonzept H2-sensors

- Applications at KIT/PS:
  All test rigs where H2-concentration in mixture has to be determined accurately in a wide concentration range.

Volume (Bomb) ≈ 8 dm³





Volume (V220) ≈ 220 m³

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