Development of a Flow Characterization Sensor for Two-Dimensional Fluid Flows

Gerald Wedel, Thomas Wiesner, Thomas Egeln

March 24th, 2025

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Topics

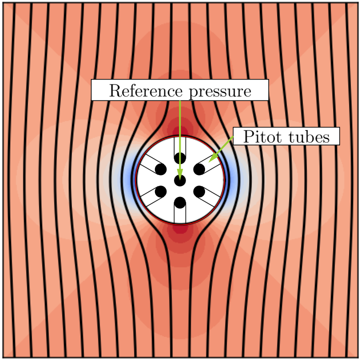
Problem definition

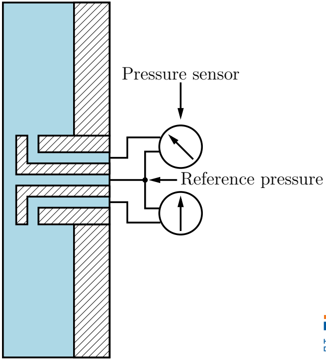
Problem definition

Flow characterization approach

- Characterisation of the flow between two adjacent plates
- Sensor has to be compatible with aqueous solutions
- Estimated speed of the flow $v = 0.1 \ldots 3\,\mathrm{m/s}$

Basic idea: measure the pressure distribution along the surface of the sensor and derive flow's velocity/angle of incidence





HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Problem definition

Flow characterization approach (cont'd)

Cylindrical sensor:

- Differential pressure sensors are employed
- 6 Pitot tubes distributed along cylinder's circumference
- 1 center Pitot tube as reference for the differential pressure sensors
- Estimated range of Reynolds number: $0 < Re < 15 \cdot 10^3$

Cylindrical sensor geometry:

+ *Simple* to fabricate
+ Well known problem in fluid dynamics
- No closed form analytical solution for pressure distribution due to **flow regimes**

HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Problem definition

Flow characterization approach (cont'd)

- Analytical solution for pressure coefficient C_p around cylinder's circumference:

$$C_p = \frac{p - p_\infty}{\frac{1}{2}\rho V^2} = 2\cos(2\theta) - 1$$

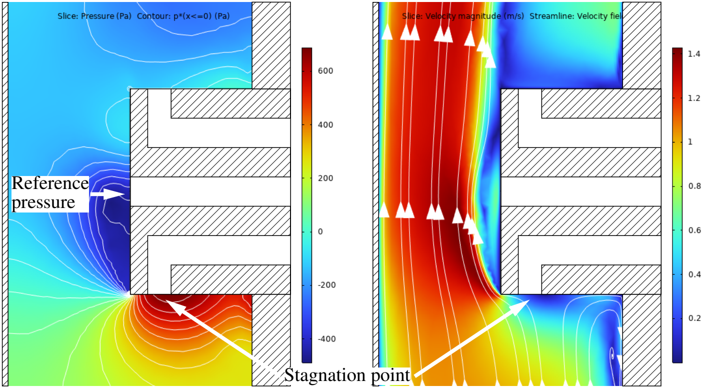
- **But:** analytical solution only holds for potential flows (without any vorticity)
- **Thus:** equation for C_p approximates the pressure well up to the point of flow separation ($0 \leq \theta \lessapprox \frac{\pi}{2}$, $\frac{3\pi}{2} \lessapprox \theta \leq 2\pi$)
- For $\frac{\pi}{2} \lessapprox \theta \lessapprox \frac{3\pi}{2}$ different flow regimes are traversed, where the pressure significantly differs from the analytical solution above [1],[2]

⇒ A suitable data evaluation strategy has to be developed!

Problem definition

Flow characterization approach (cont'd)

First simulation results: pressure (left) and velocity (right)



- Constriction between sensor and side wall ⇒ a suction region on top of the cylinder

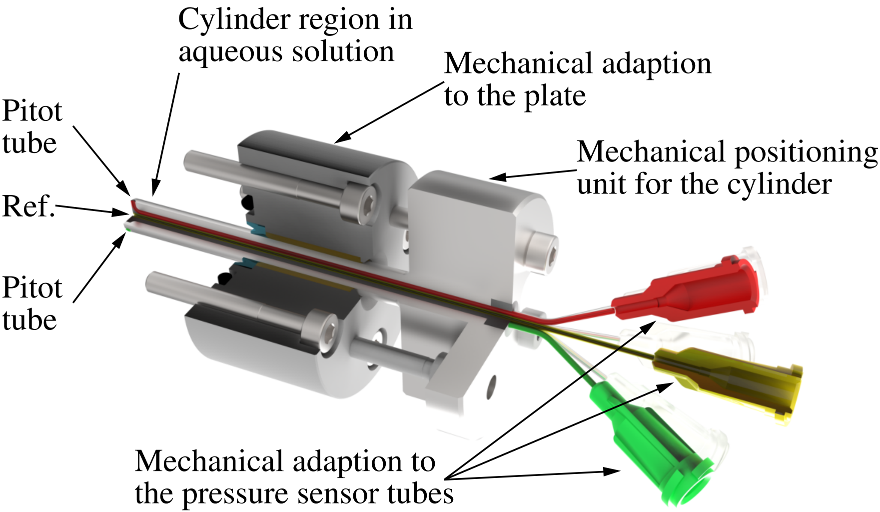
→ Reference pressure becomes negative

⇒ Positive (velocity dependent) offset!

Mechanical constructions

Mechanical constructions

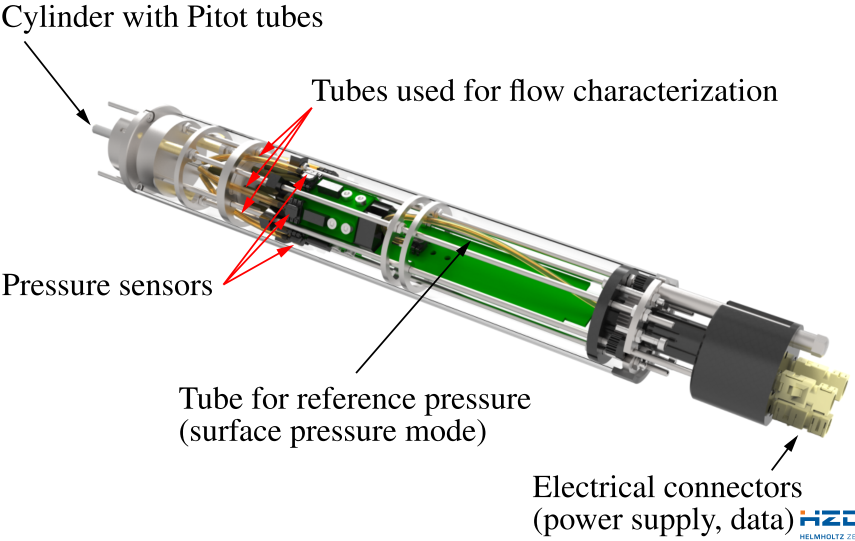
Cylinder with Pitot tubes



HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Mechanical constructions

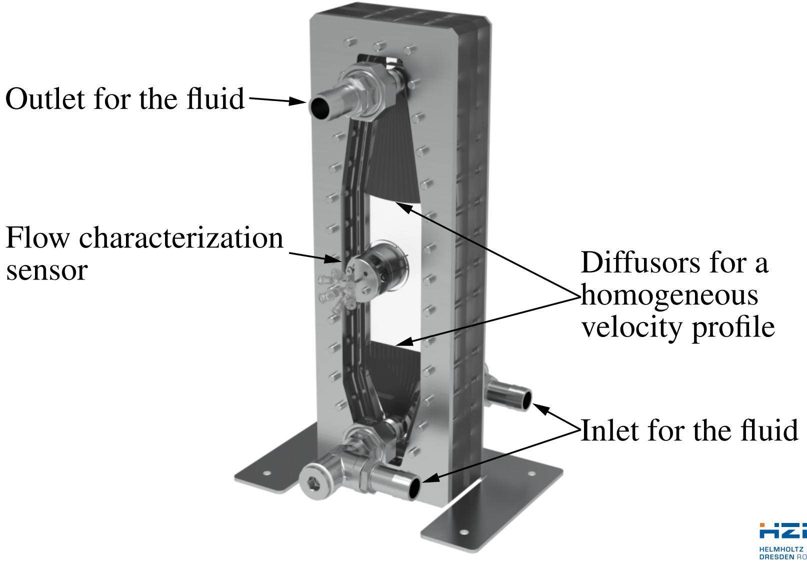
Sensor



HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Mechanical constructions

Calibration cell



The Pressure Sensors

Pressure Sensor Requirements

- Must be able to operate with in contact with liquids
- Pressure range depends on flow speed. Stagnation pressure:

$$p - p_\infty = \frac{1}{2}\rho v^2$$

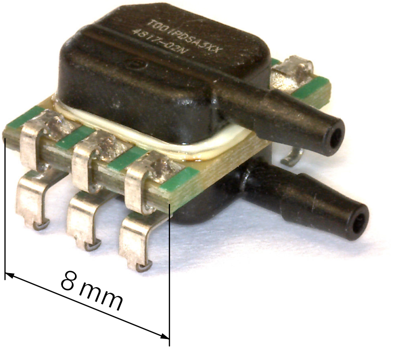
  0.1 m/s ... 3 m/s in water 5 Pa ... 4500 Pa. $\Rightarrow$ Rather low pressure range.

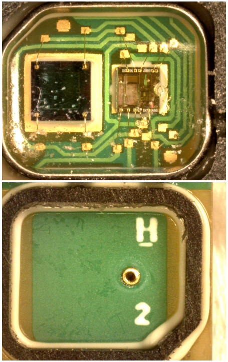
- Must be small (we need to locate many of them closely spaced)
- Not too expensive would be nice
- Easy readout is a plus.

$\Rightarrow$ Only a few off-the-shelf types available

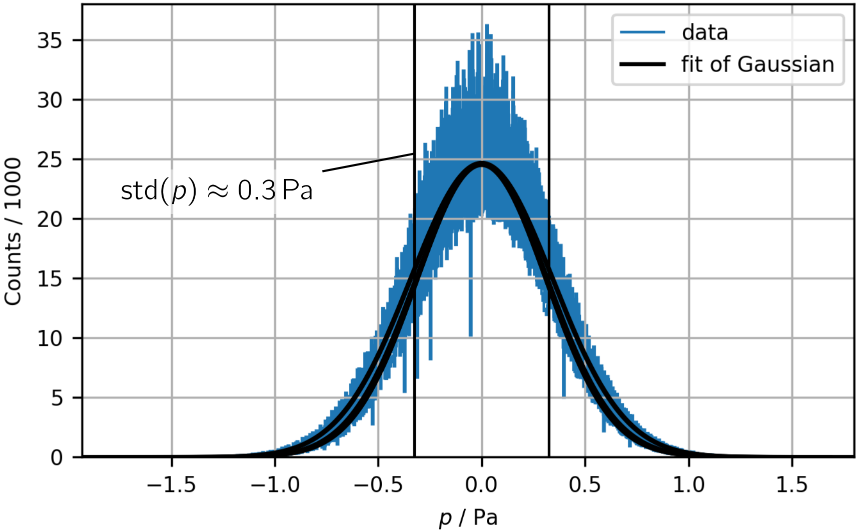
Honeywell ABP2 Series

- May operate with liquid contact
- ±6895 Pa (±1 psi)
- ≈ 200 Hz sampling rate
- Internal ADC, 24 bit
- SPI or I^2C interface



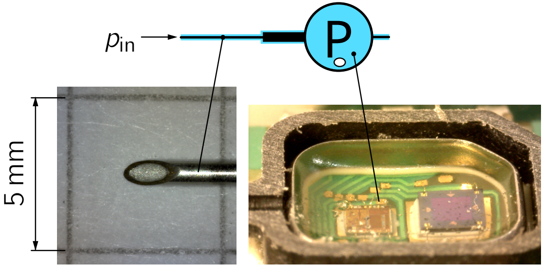


Histograms at $\Delta p = 0\,\text{Pa}$ of 5 Sensors



Frequency Response

Bandwidth Limitations

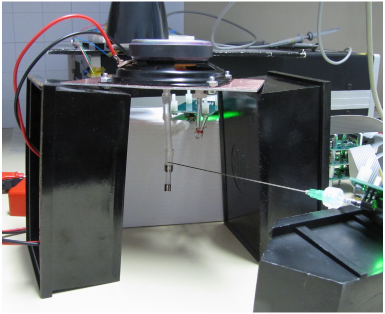


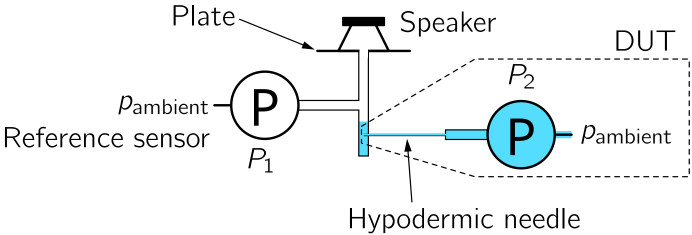
- Compliance of tubing, pressure sensor, trapped air
- Mass of liquid
- Friction in liquid

⇒ Spring, mass, damper system as 1$^{\text{st}}$ order approximation.

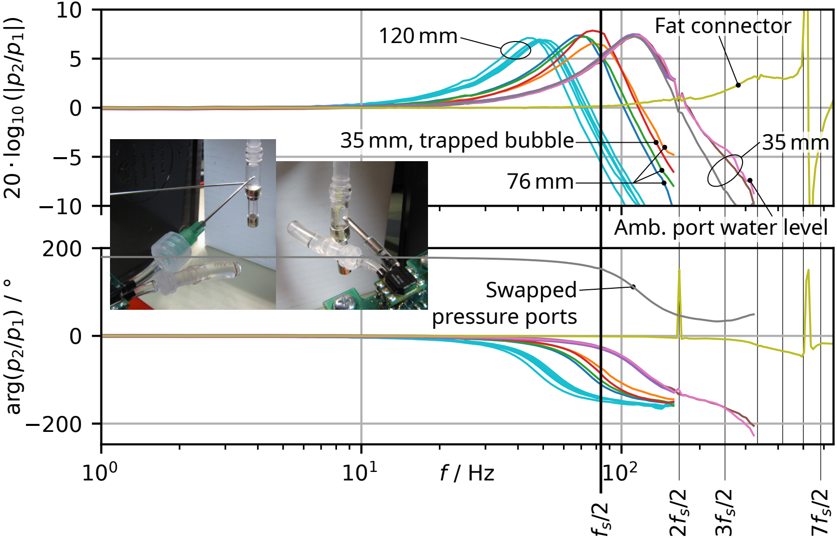
Dr. Gerald Wedel, Dr. Thomas Wiesner, Thomas Egeln | Central Department of Research Technology | http//www.hzdr.de

Setup for Frequency Response Tests





Measurement Results, misc.



Media Compatibility Tests

Filling of Sensors

Why?

Because a liquid/gas interface causes

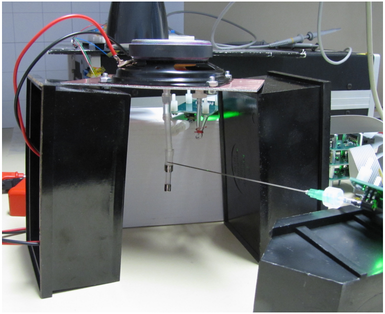
- a pressure change due to the meniscus curvature
- pressure hysteresis due to contact angle hysteresis

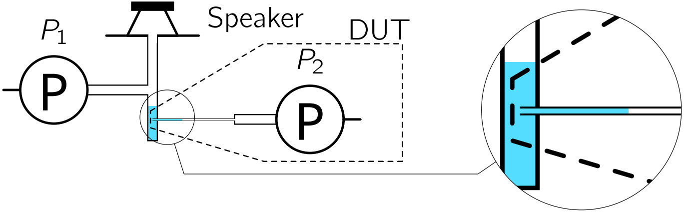
How?

The sensor ports are very small. $\Rightarrow$ Evacuation and filling in vacuum.

HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

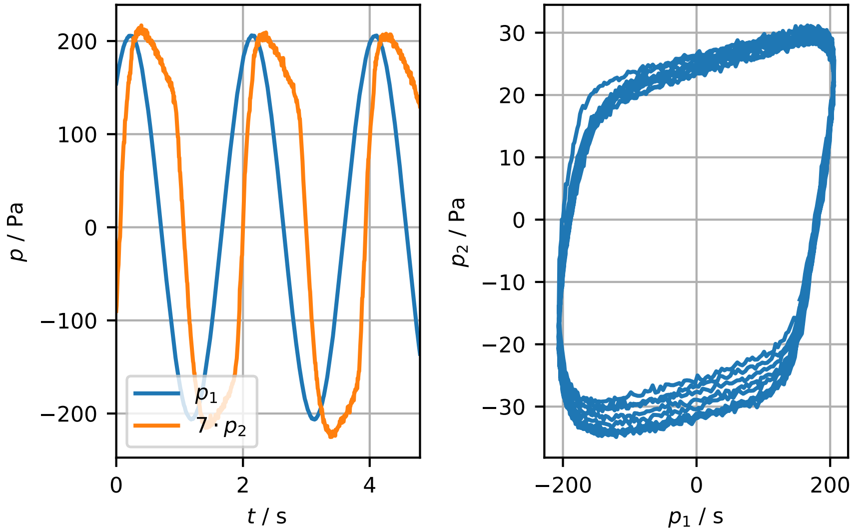
Test of Hysteresis Effects





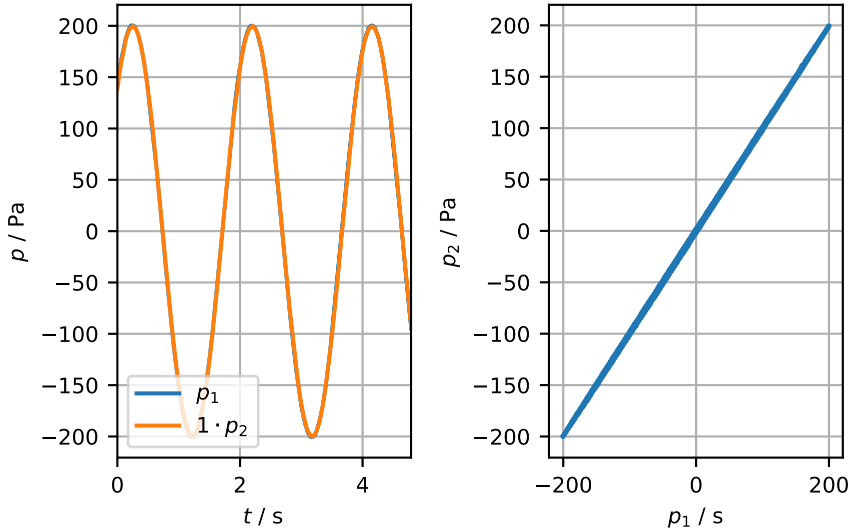
HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Hysteresis: Unfilled sensor



HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

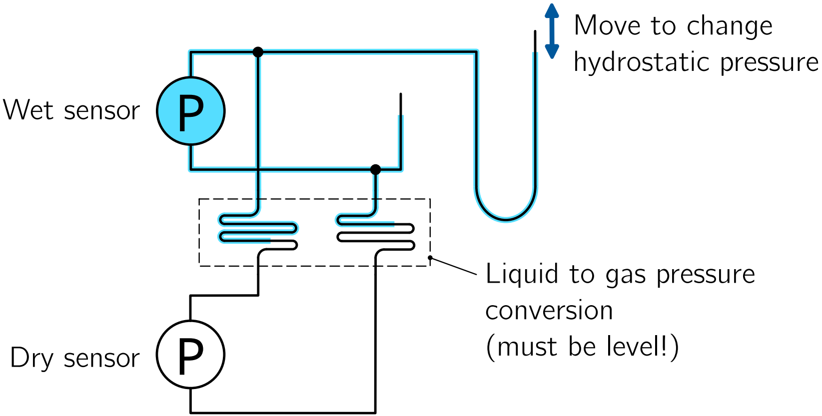
Hysteresis: Filled sensor



Dr. Gerald Wedel, Dr. Thomas Wiesner, Thomas Egeln | Central Department of Research Technology | http//www.hzdr.de

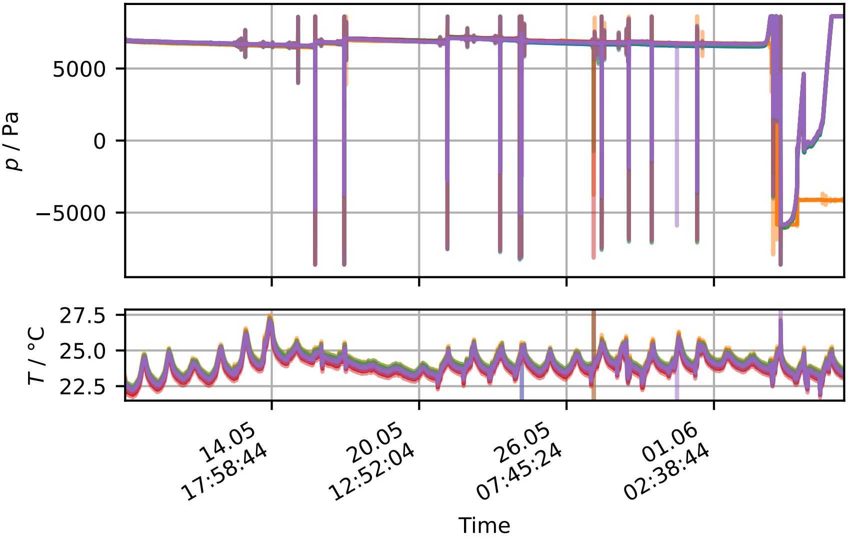
Long Term Test Setup

Comparison of wet and dry (expected to not get damaged) sensors with varying input pressures.



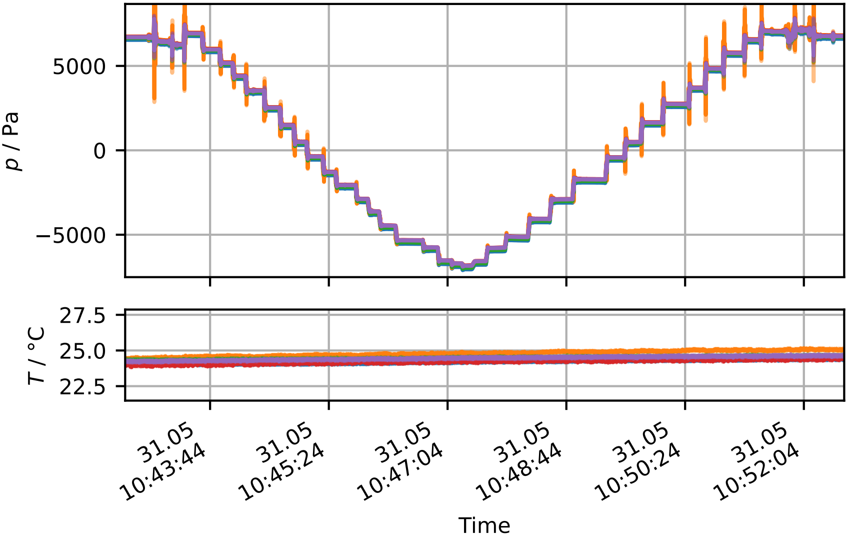
Dr. Gerald Wedel, Dr. Thomas Wiesner, Thomas Egeln | Central Department of Research Technology | http//www.hzdr.de

Results



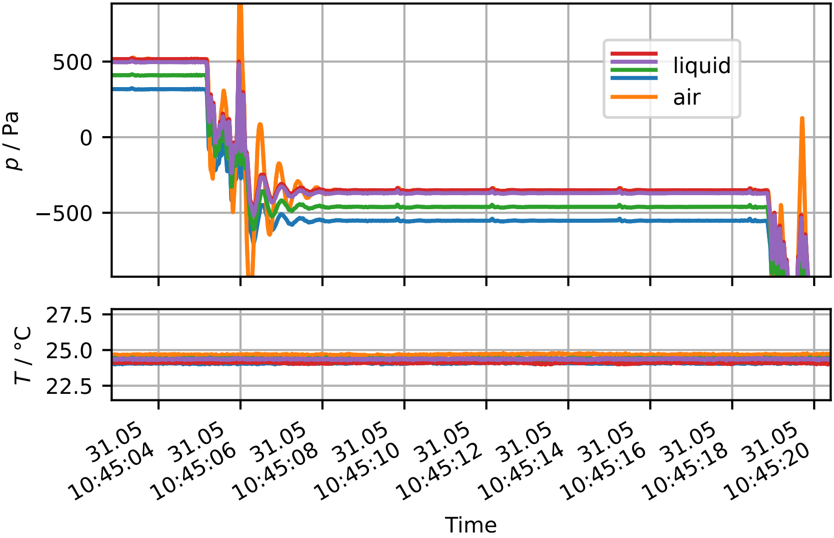
HZDR
HELMHOLTZ ZENTRUM
DRESDEN ROSSENDORF

Results



5000
0
−5000
p / Pa
27.5
25.0
22.5
T / °C
31.05 10:43:44
31.05 10:45:24
31.05 10:47:04
31.05 10:48:44
31.05 10:50:24
31.05 10:52:04
Time

Results

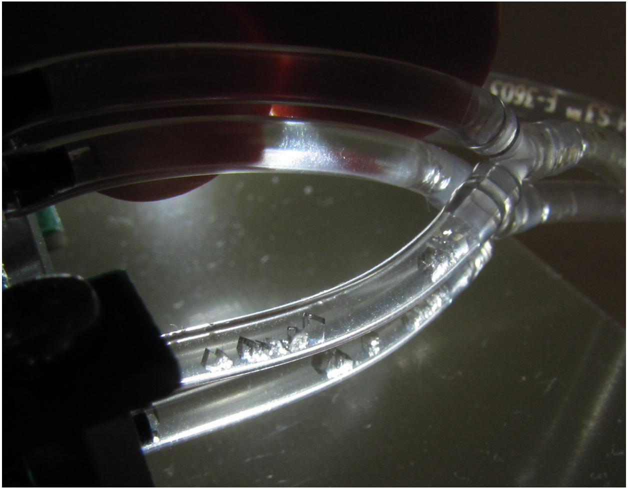


500
0
−500
p / Pa
liquid
air
27.5
25.0
22.5
T / °C
31.05 10:45:04
31.05 10:45:06
31.05 10:45:08
31.05 10:45:10
31.05 10:45:12
31.05 10:45:14
31.05 10:45:16
31.05 10:45:18
31.05 10:45:20
Time

Tubing Material Tests

Effect of Water Diffusion

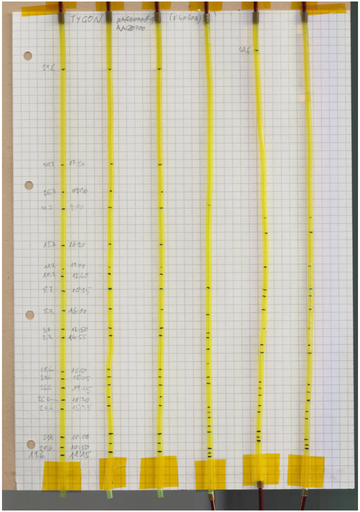
- Sensor connection is like a blind hole
- Water leaves, dissolved material stays in ⇒ not good!



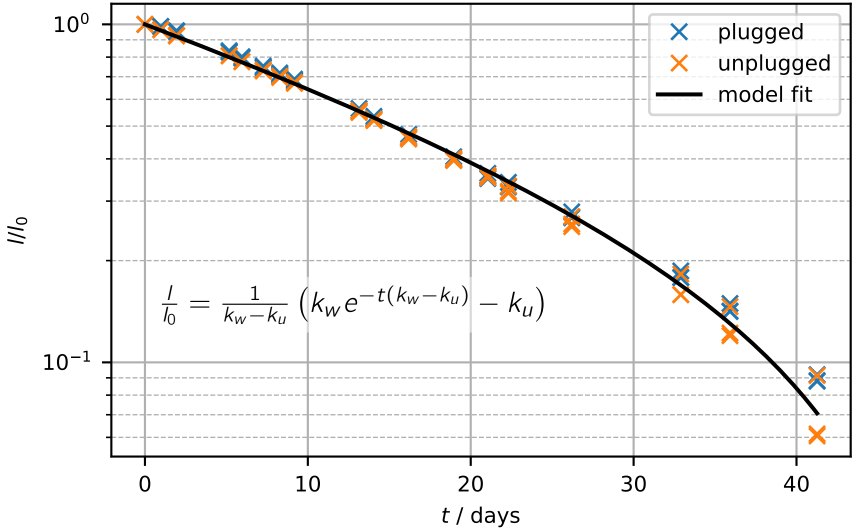
Water Diffusion

Tested Materials

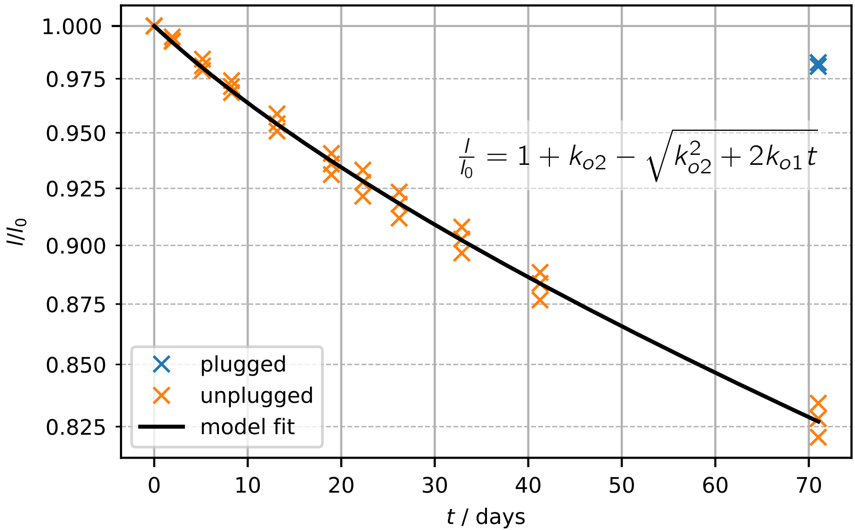
- Tygon E3603® (ACF00002), $d_i = 1.6\,\text{mm}$, $d_o = 3.2\,\text{mm}$
- Versilon™ C-210-A (AEM02002), $d_i = 1.6\,\text{mm}$, $d_o = 3.2\,\text{mm}$
- Tygon® F-4040-A (AAG00700), $d_i = 2\,\text{mm}$, $d_o = 3.56\,\text{mm}$
- Versilon™ SE-200 (AJD00002), $d_i = 1.6\,\text{mm}$, $d_o = 3.2\,\text{mm}$
- Carl Roth Rotilabo® 9557.1, silicone tubing, $d_i = 1.5\,\text{mm}$, $d_o = 3.5\,\text{mm}$



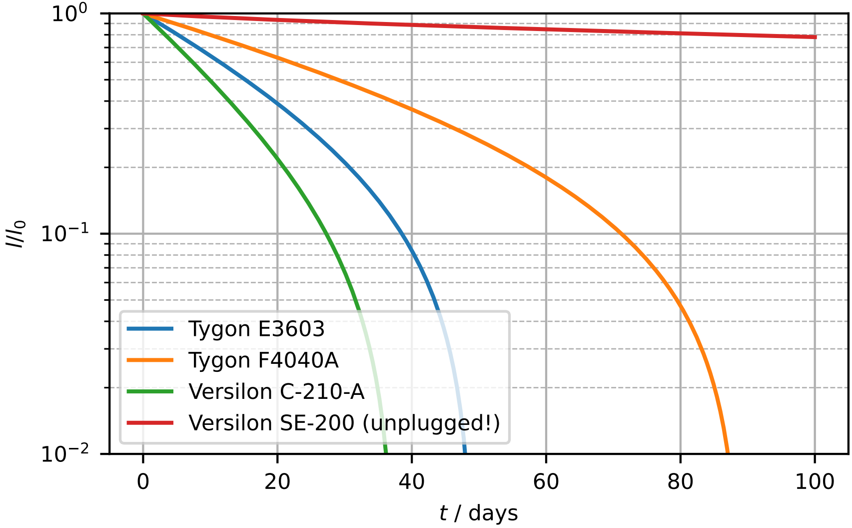
Results Tygon E3603



Results Versilon SE-200



Comparison



;

HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

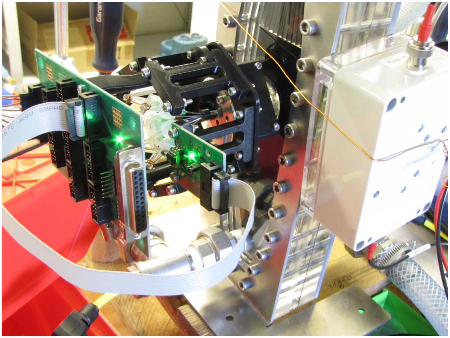
Intermediate Summary

- Filling of sensors to avoid phase boundaries is necessary.
- Expected bandwidth on the order of 100 Hz.
- No anti-aliasing filter in the ABP2 pressure sensor.
- Sensitive to trapped bubbles and setup variations.
- Sensors in solution drifted apart 200 Pa over the course of about a month.
  - Sensor damage or depositions? Unclear.
  - Short time stability seems sufficient.
- Tubing must be selected carefully
  - Tygon E3603® is very supple but has high water diffusion and tends to creep.
  - Versilon™ SE-200 has low diffusion but difficult to handle.

Measurements/data evaluation

Measurements/data evaluation

Measurement setup

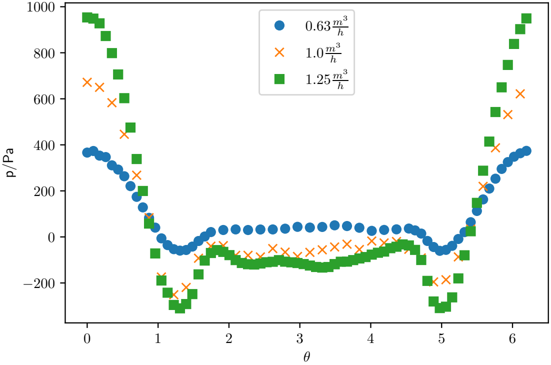


- Prototype of the sensor used for first measurements at the calibration cell
- Only one Pitot tube (plus reference tube) is employed
- Sensor prototype can be rotated → pressure distribution around cylinder's circumference is measured for different flow rates

HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Measurements/data evaluation

First measurements



- Measured at 3 different flow rates
- Mean values are shown (averaged over 10k samples)
- Agrees with theory/literature with increasing flow rates:
  1. Higher pressure at stagnation point ($\theta = 0$)
  2. In rear region, pressure decreases (flow regimes)

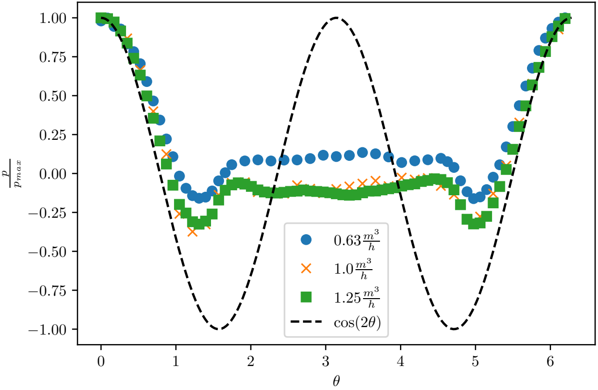
Measurements/data evaluation

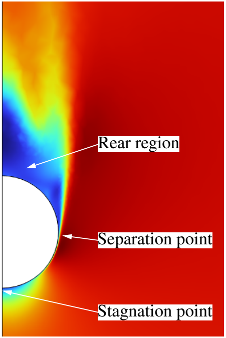
How to estimate the velocity/angle of incidence?

- Sensor consists of 6 Pitot tubes $\rightarrow$ 6 values on the pressure distribution
- Several approaches are possible:
  1. Usage of a Lookup-table plus interpolation/optimizer
  2. AI approach
  3. Development of a model equation plus optimizer
- Option 1 & 2 need a lot of measurement data
- Option 3 needs less measured data and is partially physically motivated

Measurements/data evaluation

Development of the model equation



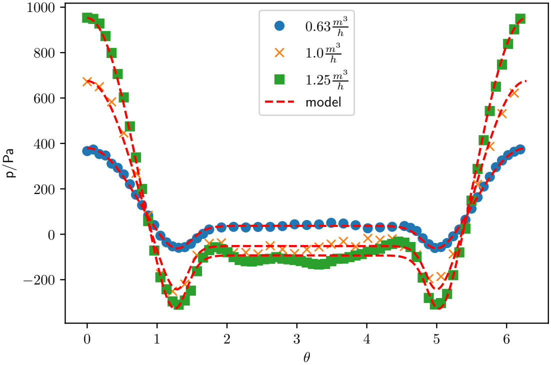


1. Prior the separation point of flow, a cos-like behaviour is seen
2. The remaining region (rear region of the sensor) is approximated by a plateau
3. Weighting function is used to model the transition

HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Measurements/data evaluation

Measurements vs. model equation



- Transition between cos and plateau region sufficiently good modelled
- Currently 5 model parameters (reduction to 3 in progress)
  - ⇒ Model resembles the shape of measured pressures

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF
Member of the Helmholtz Association
Dr. Gerald Wedel, Dr. Thomas Wiesner, Thomas Egeln | Central Department of Research Technology | http//www.hzdr.de

Thank you for your attention!

Bibliography

- "Frontmatter". In: *Incompressible Flow*. John Wiley & Sons, Ltd, 2013, pp. i–xix. ISBN: 9781118713075. DOI: https://doi.org/10.1002/9781118713075.fmatter. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/9781118713075.fmatter. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/9781118713075.fmatter.
- William W. Willmarth and Timothy Wei. "Static Pressure Distribution on Long Cylinders as a Function of the Yaw Angle and Reynolds Number". In: *Fluids* 6.5 (2021). ISSN: 2311-5521. DOI: 10.3390/fluids6050169. URL: https://www.mdpi.com/2311-5521/6/5/169.