Thermo-Fluidic Impulse Response and TOF Analysis of a Pulsed Hot Wire

M.Sc. Okan Ecin
Chair for Electronic Components and Circuits
University Duisburg-Essen, Germany
October 27th, 2011
COMSOL Conference 2011
Ludwigsburg, Germany

UNIVERSITÄT DUISBURG ESSEN

Outline

- Introduction
- Fundamentals to Thermal Time-of-Flight (TOF)
- Experimental Setup vs. COMSOL Model
- Flow Sensor as an LTI-System
- Results
- Conclusion

Introduction

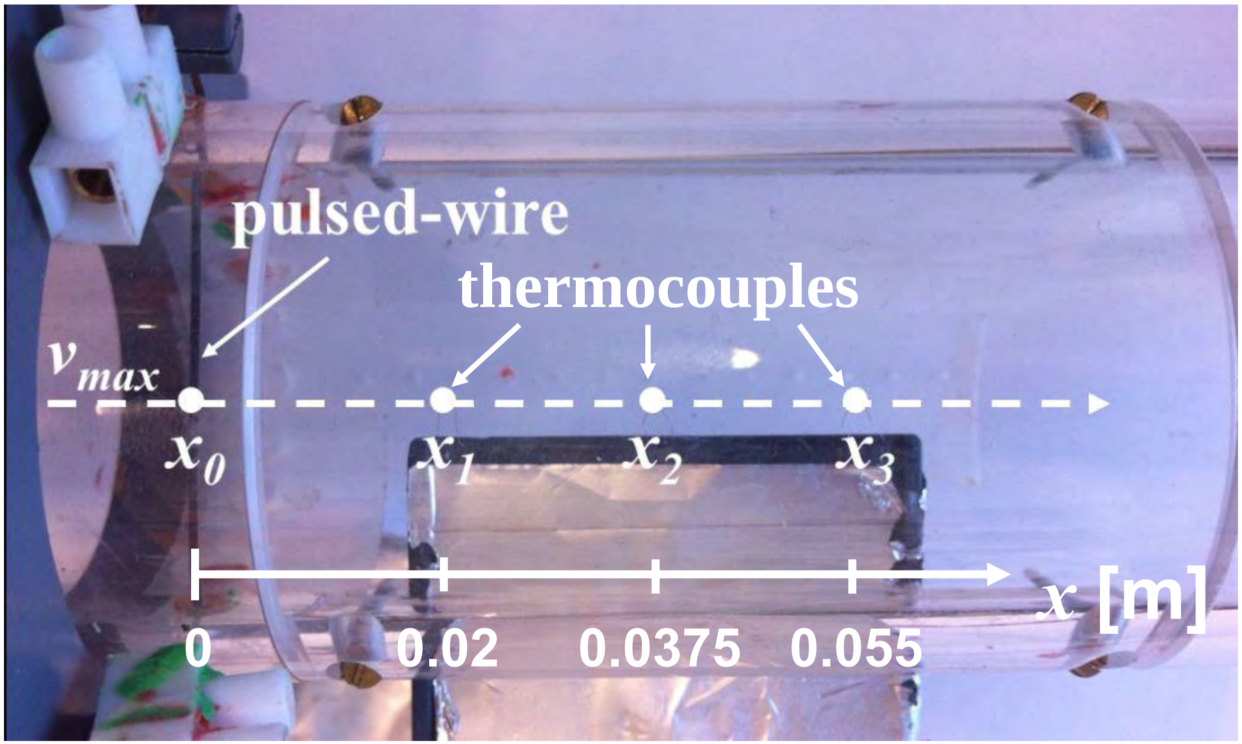
- <u>flow measurement principle for quite a number of fluids</u>
  - ➔ controlling volume flow rates of fluids
  - ➔ investigations for four fluids in a velocity range between 0.01 m/s and 1.72 m/s

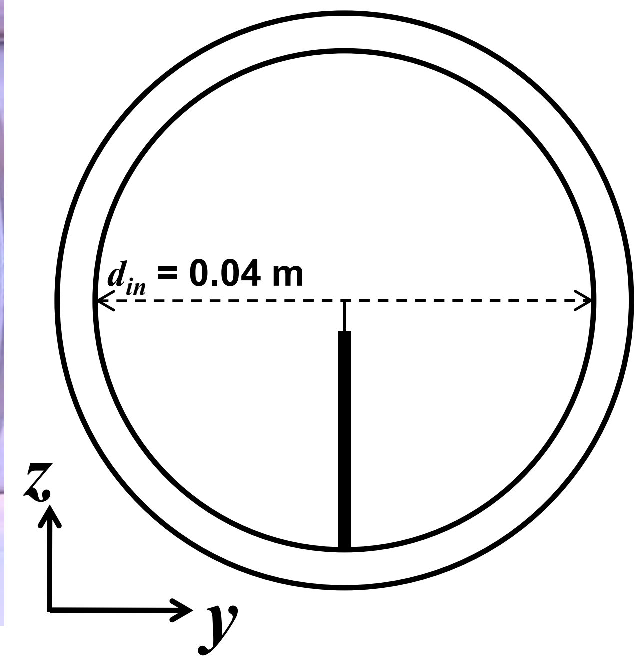
Fundamentals to Thermal Time-of-Flight (TOF)

- heat pulse generation
  - ➔ electrical signal is applied at the hot wire
  - ➔ square waveform with pulse width of 0.1 s and period of 10 s
  - ➔ system identification by obtaining the impulse response

Experimental Setup vs. COMSOL Model…

experimental setup of the thermal Time-of-Flight flow sensor:



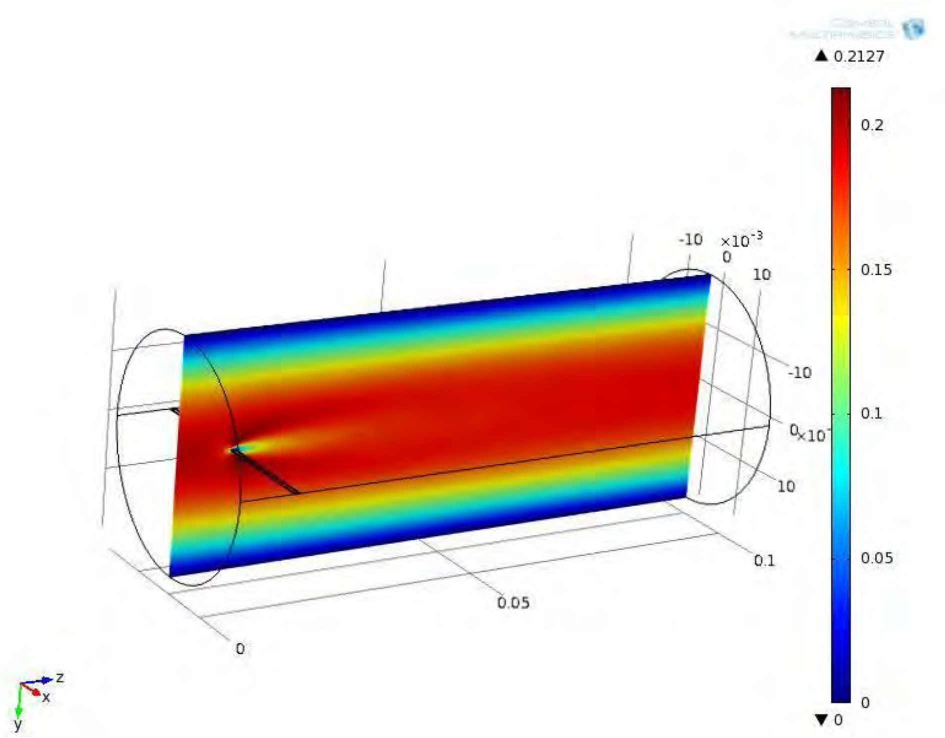


system identification ➔ $V_{out}(t) \approx h(t) = f(v, x, \alpha)$

v = flow velocity
x = flight distance
α = thermal diffusivity

…Experimental Setup vs. COMSOL Model…

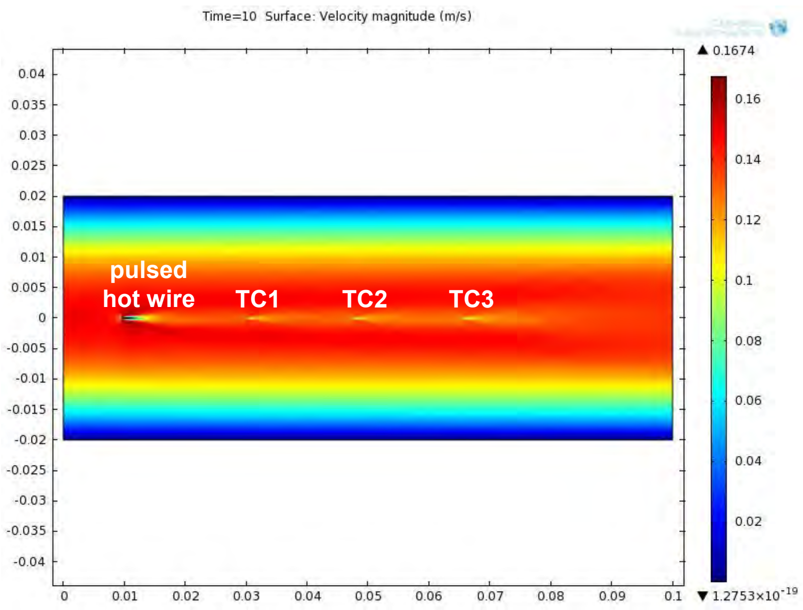
Modeling in COMSOL Multiphysics:



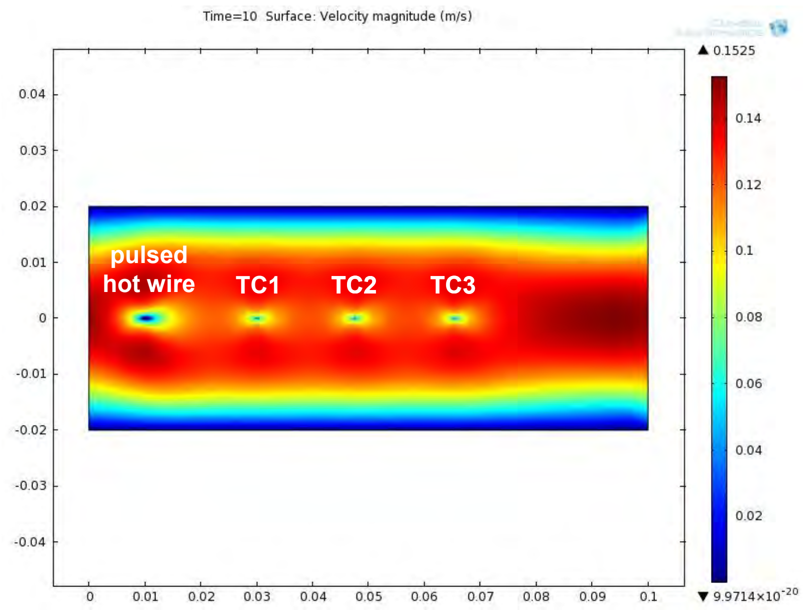
- Laminar Flow mode (spf)
- Joule Heating mode (jh)
  - heat diffusion
  - heat convection
  - electric currents
- filament
- thermocouples
- stationary 3D
- stationary and transient 2D
- fluids: - air
  - helium
  - water
  - oil

…Experimental Setup vs. COMSOL Model

velocity distribution for water at v_{mean} = 0.1 m/s



velocity distribution for oil at v_{mean} = 0.1 m/s



filament: tungsten (0.2 mm x 0.8 mm)

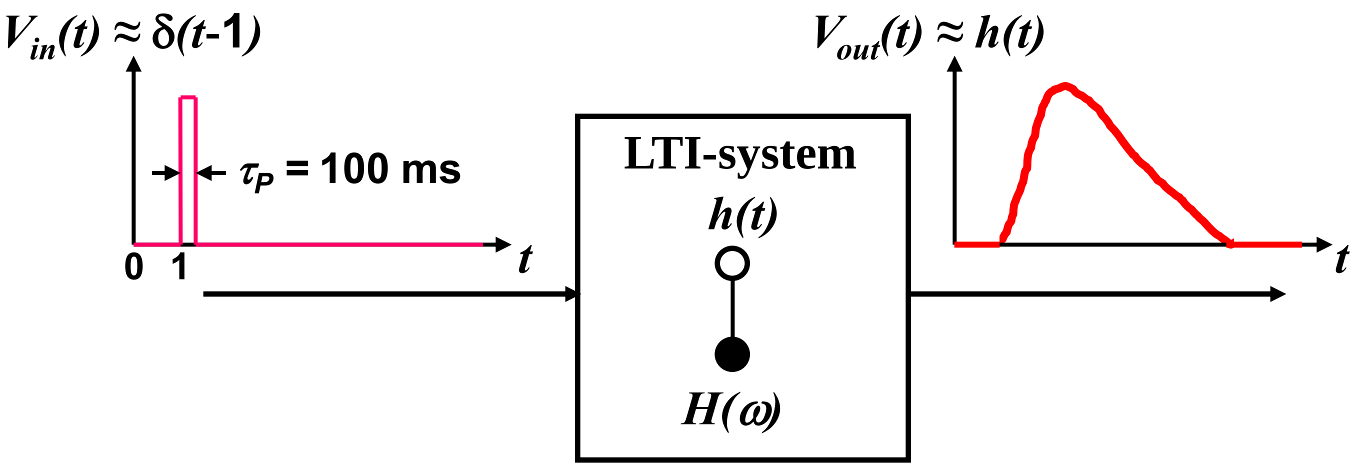
thermocouples: nickel alloy (d_{TC} = 50 μm)

kinematic viscosity of water: ν_{wat} = 1e-6 m²/s

kinematic viscosity of oil: ν_{oil} = 8.9e-4 m²/s

Flow Sensor as an LTI-System…

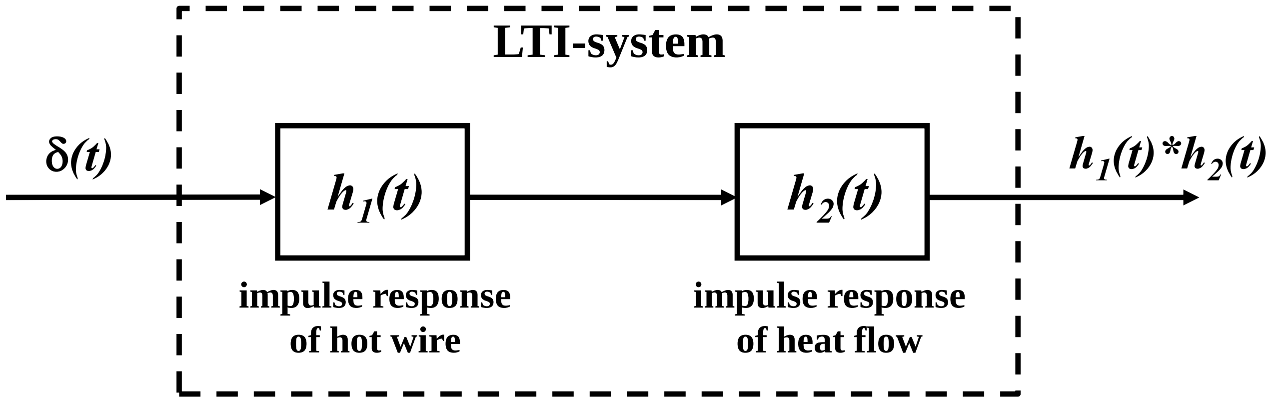
„Thermal Time-of-Flight“ (TTOF) flow sensor:



thermo-fluidic impulse response of the TTOF flow sensor

- Ecin at al., “System-theoretical analysis and modeling of pulsed thermal Time-of-Flight flow sensor“, The IEEE 7th Conference on Ph.D. Research in Microelectronics and Electronics (PRIME), Madonna di Campiglio, Italy July 3-7,2011.

Two subsystems in series:



pulsed-wire equation:

$$\frac{T_p(t) - T_a}{T_{p,m} - T_a} = \exp\left(-\frac{t}{M_p}\right)$$

advection-diffusion equation:

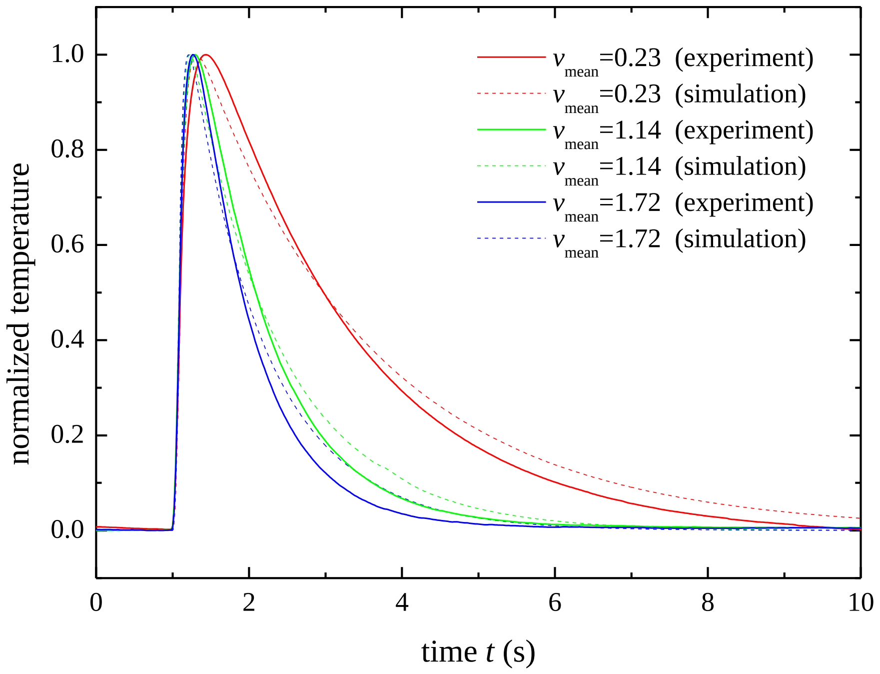
$$T(x,t) = \frac{C}{t \cdot \sqrt{4\pi\alpha t}} \cdot \exp\left(\frac{(x - vt)^2}{4\alpha t}\right)$$

- H. H. Bruun, Hot-Wire Anemometry: Principles and Signals, Oxford University Press Inc., New York, 1995.
- Ecin at al., “Signal characterization of a pulsed-wire and and heat flow system at a flow sensor“, The IEEE 20th European Conference on Circuit Theory and Design (ECCTD), Linköping, Sweden August 29-31,2011.

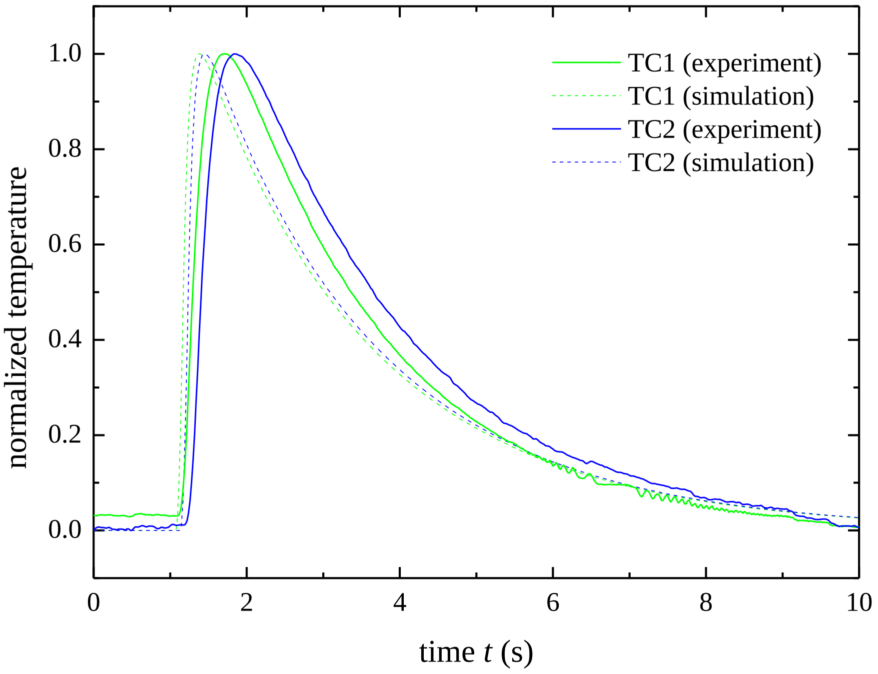
Results…

Experiment vs. Simulation:

impulse response at pulsed wire for air



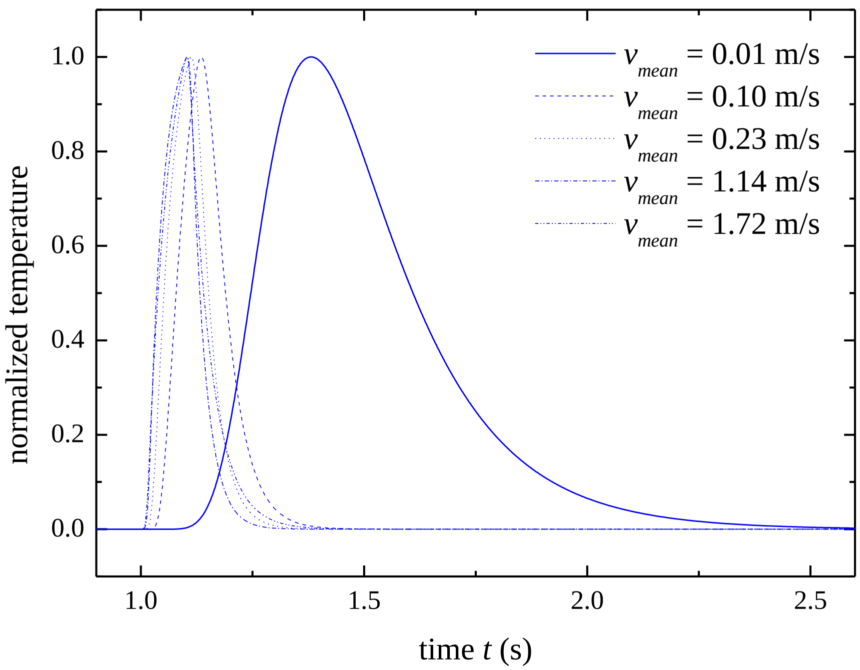
signal outputs at TC1 and TC2 for air



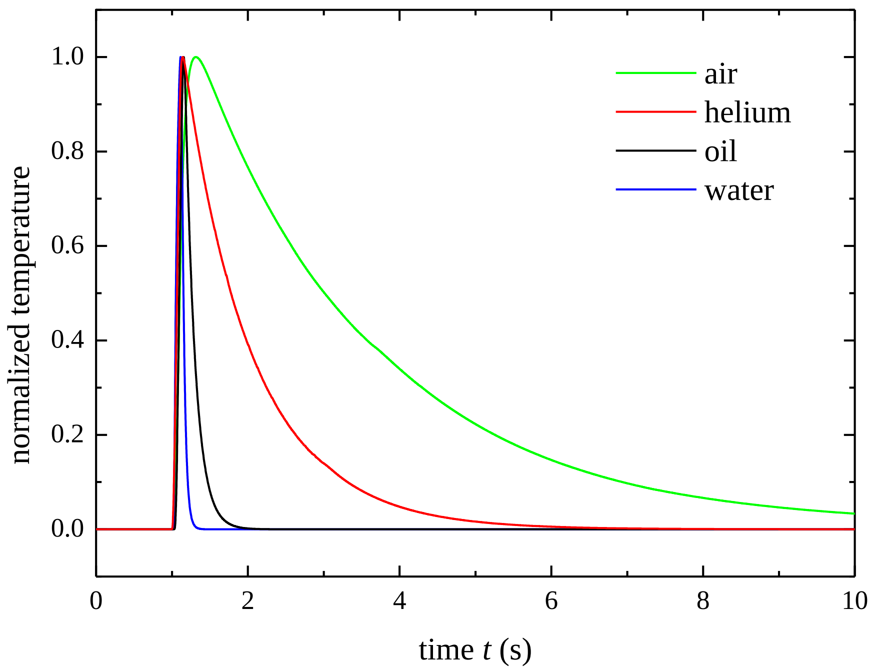
...Results...

Thermo-fluidic impulse responses at the pulsed hot wire:

water at several flow velocities

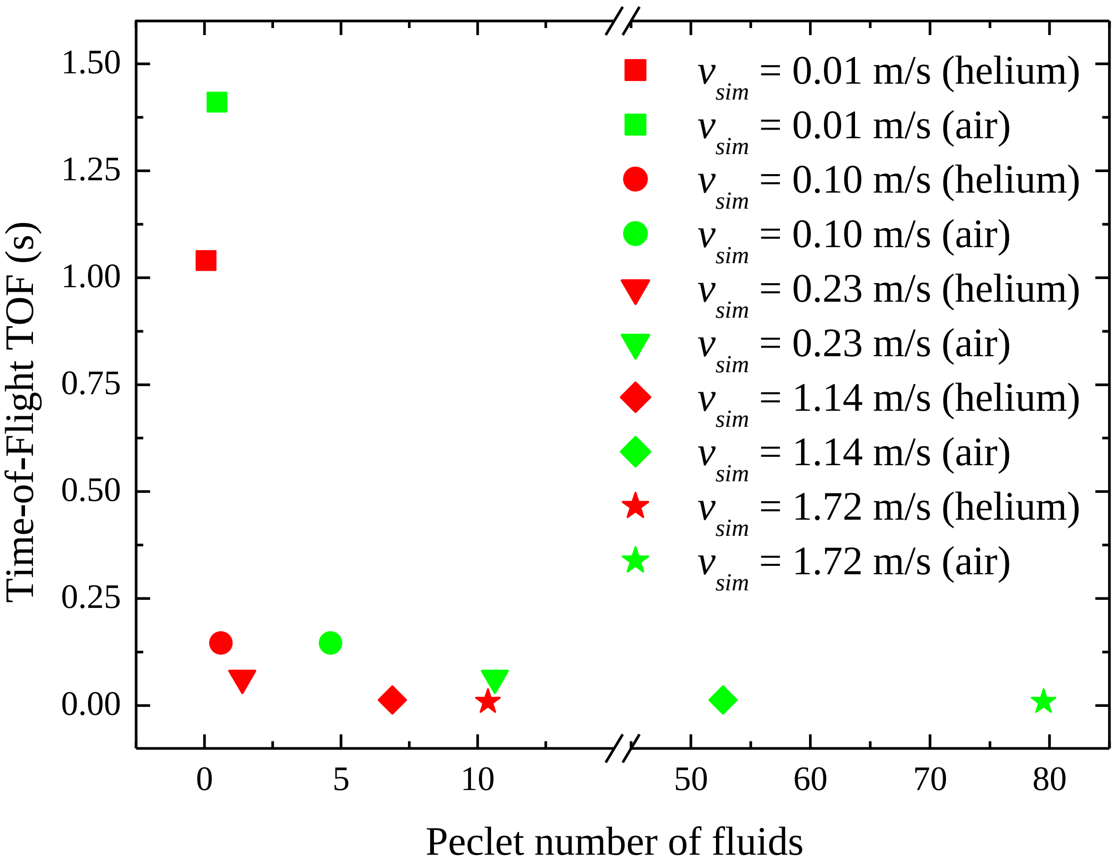


all fluids at v_{mean} = 0.23 m/s



...Results...

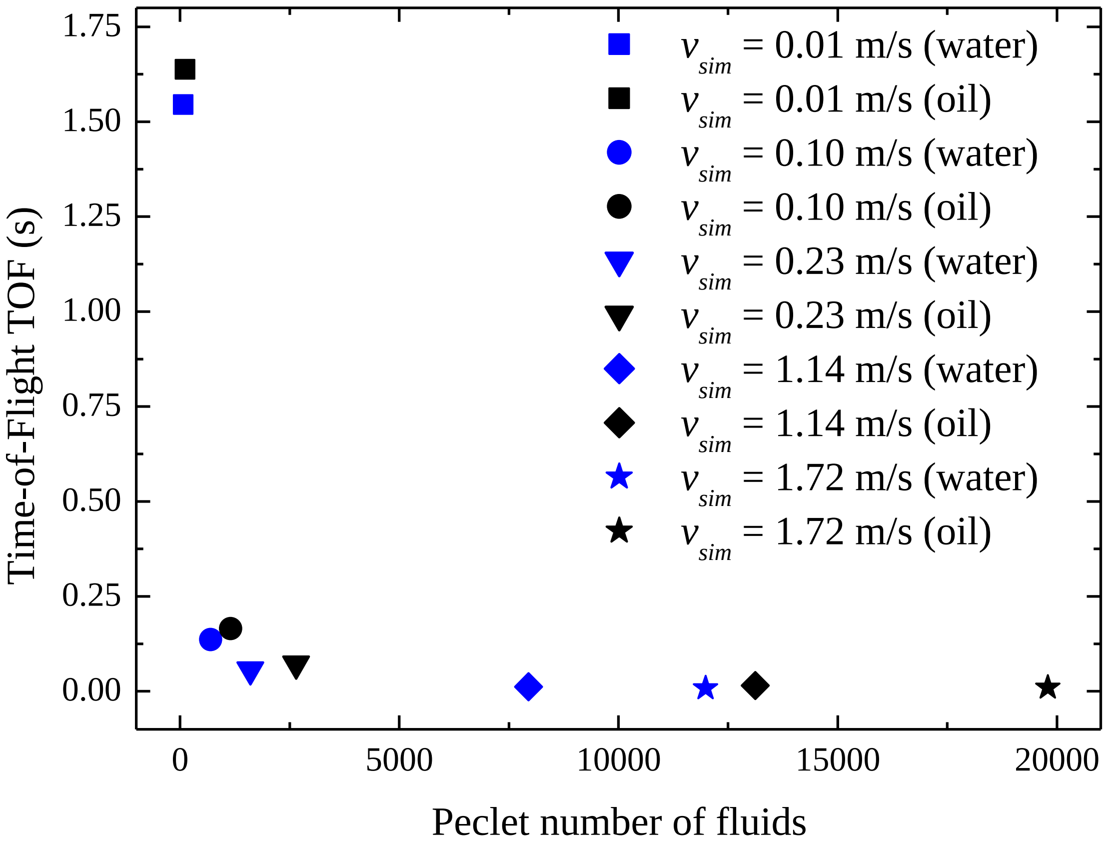
Time-of-Flight of the heat pulse in gases:



- **signal outputs at TC1 and TC2 are measured**
- **TOFs according to the distance are obtained by applying the crosscorrelation method to the signal outputs at TC1 and TC2**
- **Peclet number as the ratio of heat convection to heat diffusion**

...Results...

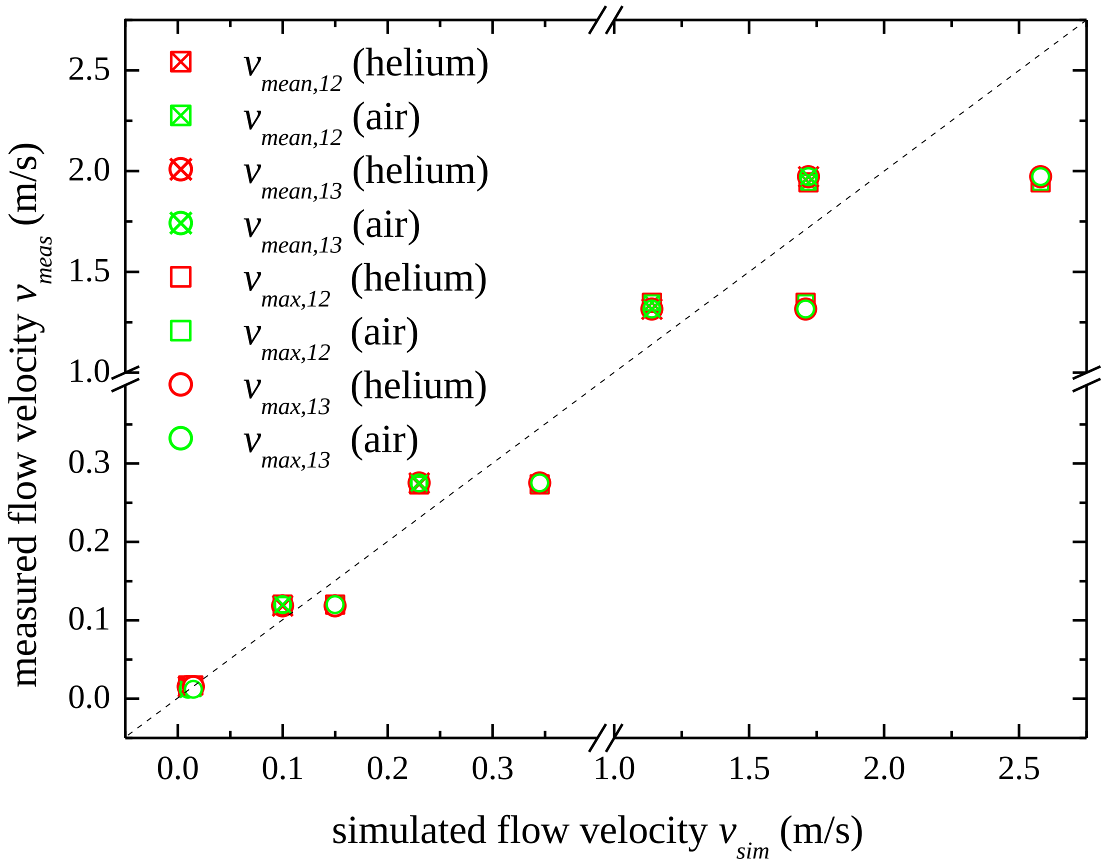
Time-of-Flight of the heat pulse in liquids:



- **heat pulse in oil is basically slower than in water**
- **kinematic viscosity of oil is greater**
- **with increasing velocity the TOF difference between oil and water decreases**

…Results…

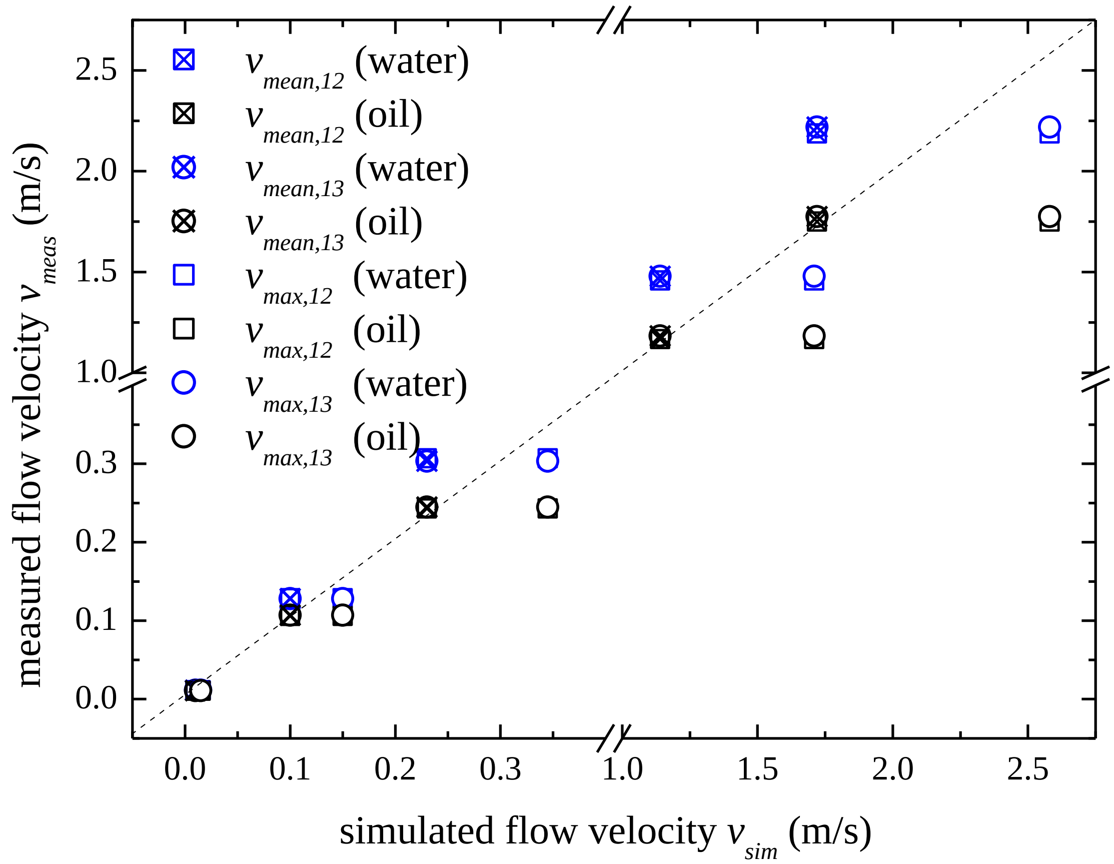
Flow velocity measurement for gases:



- **signal outputs at TC1, TC2 and TC3 are measured**
- **TOFs according to the distances are obtained by applying the crosscorrelation to the signal outputs at TC1->TC2 and TC1 -> TC3**
- **variation of the mean and maximum flow velocity**

...Results

Flow velocity measurement for liquids:



- **signal outputs at TC1, TC2 and TC3 are measured**
- **TOFs according to the distances are obtained by applying the crosscorrelation to the signal outputs at TC1->TC2 and TC1 -> TC3**
- **variation of the mean and maximum flow velocity**

Conclusion

- TTOF flow sensor is regarded as an LTI-system
- simulation model matches well with experiment for air
- flow sensor model applied on further fluids
- thermo-fluidic impulse response depends on flow velocity
- thermodynamic parameters correspond signal parameters
- TOF is manipulated by heat diffusion part

End

Appendix

thermodynamic and fluidic parameters of the investigated fluids:

	helium	air	water	oil
Pr	0.6865	0.7081	6.991	10243
ν	1.14e-4	1.53e-5	1e-6	8.9e-4
α	1.59e-4	2.16e-5	1.44e-7	8.7e-8
c_p	5.193	1.0064	4.185	1.88
ρ	0.1758	1.1885	998.21	887.6
λ	0.1513	2.59e-2	6e-1	0.145