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

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Outline

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

• flow measurement principle for quite a number of fluids
  ➤ 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

- heat pulse transfer
  - forced heat convection, heat advection: causes time shift of the heat pulse, since heat is carried along with the flowing fluid (does not depend on medium!)
  - heat diffusion: causes heat pulse dispersion (does depend on medium!)

- heat pulse detection
  - detection of heat pulses after a certain flight distance
  - thermocouples measure the thermo-fluidic signals
Experimental Setup vs. COMSOL Model…

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

- **Pulsed-wire thermocouples**
- Flow velocity: \( v \)
- Flight distance: \( x \)
- Thermal diffusivity: \( \alpha \)

**System identification**

\[ V_{\text{out}}(t) \approx h(t) = f(v, x, \alpha) \]

- \( d_{\text{in}} = 0.04 \text{ m} \)
- \( x_0, x_1, x_2, x_3 \)

\[ 0 \quad 0.02 \quad 0.0375 \quad 0.055 \]
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 $v_{\text{mean}} = 0.1 \text{ m/s}$

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

- filament: tungsten (0.2 mm x 0.8 mm)
- thermocouples: nickel alloy ($d_{TC} = 50 \mu m$)
- kinematic viscosity of water: $\nu_{\text{wat}} = 1e^{-6} \text{ m}^2/\text{s}$
- kinematic viscosity of oil: $\nu_{\text{oil}} = 8.9e^{-4} \text{ m}^2/\text{s}$
Flow Sensor as an LTI-System...

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

\[ V_{in}(t) \approx \delta(t-1) \]

\[ V_{out}(t) \approx h(t) \]

LTI-system

\[ h(t) \]

\[ H(\omega) \]

thermo-fluidic impulse response of the TTOF flow sensor

Two subsystems in series:

LTI-system

$h_1(t)$

$h_2(t)$

$h_1(t) * h_2(t)$

impulse response of hot wire

impulse response of heat flow

pulsed-wire equation:

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

advection-diffusion equation:

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

Results...

Experiment vs. Simulation:

impulse response at pulsed wire for air

signal outputs at TC1 and TC2 for air

\[ v_{\text{mean}} = 0.23 \text{ (experiment)} \]
\[ v_{\text{mean}} = 0.23 \text{ (simulation)} \]
\[ v_{\text{mean}} = 1.14 \text{ (experiment)} \]
\[ v_{\text{mean}} = 1.14 \text{ (simulation)} \]
\[ v_{\text{mean}} = 1.72 \text{ (experiment)} \]
\[ v_{\text{mean}} = 1.72 \text{ (simulation)} \]
...Results...

Thermo-fluidic impulse responses at the pulsed hot wire:

- **water at several flow velocities**
- **all fluids at $v_{\text{mean}} = 0.23$ 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
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
Thank You For Your Attention
Appendix

thermodynamic and fluidic parameters of the investigated fluids:

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<th>helium</th>
<th>air</th>
<th>water</th>
<th>oil</th>
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<tr>
<td>Pr</td>
<td>0.6865</td>
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<td>ν</td>
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