Simulation of MEMS Based Flexible Flow Sensor for Biomedical Application

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Presentation Overview

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• Hot-wire Anemometry Principle
• Literature Survey
• Sensor Development
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  • Substrate Selection
  • Sensor Geometry
• Steady State Analysis
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  • Electrical Potential distribution
  • Velocity distribution
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Aim

Development of MEMS Based Flexible Flow Sensor for Health Care Monitoring

Catheter Pathway through Aorta

Catheter with sensor against blood flow direction

SENSOR SETUP
Hot-wire Anemometry Principle

Principle (**Hot-wire Anemometer**):

Fluid velocity is determined by the amount of heat dissipated in the fluid from the electrically heated sensing element exposed in the fluid medium.

Types:

1) Single Hot Wire Anemometer      2) Multi Hot wire Anemometer
Heat transfer mechanisms: Conduction and Convection.

At equilibrium: Input power \((I^2R_w)\) = power lost \(h.A_w(T_w-T_f)\) to convective heat transfer

\[
I^2 R_w = h.A_w(T_w - T_f)
\]

Wire resistance \(R_w\) at temperature \(T_w\) is given by:

\[
R_w = R_{Ref}[1 + \alpha(T_w - T_{Ref})]
\]

According to King's law, The heat transfer coefficient \(h\) is a function of fluid velocity \(v_f\)

\[
h = a + b.v_f^c
\]

Hence, fluid velocity is given by:

\[
v_f = \left\{\left[\frac{I^2 R_{Ref}[1 + \alpha(T_w - T_{Ref})]}{A_w(T_w - T_f)} - a}{b}\right]^{1/c}\right\}
\]

\[I^2 \alpha v_f^{1/3}\]
• **Shear Stress Sensor** –
  1) Disturbed blood flow at arterial bifurcations is considered to be an inducer of vascular oxidative shear stress that promotes the initiation and progression of **atherosclerosis**.
  2) A micromachined flow shear-stress sensor based on thermal transfer principles have been developed by Tzung k. Hsiai et al.

• **Pressure sensor** –
  1) Disposable CMOS Catheter-tip Pressure Sensor For Intracranial Pressure Measurement by Li-Anne Liew et al, University of Colorado, USA.
  2) Silicon flow sensor with on-chip CMOS readout electronics over catheter surface have been reported by R. Kersjes et al.
  3) A combination of blood pressure/flow/oxygen sensor chip has been developed at the Delft University of Technology that can be fitted to a catheter.

• **Our Method** –
  Development of flow sensor for detection of stenosis by measuring the change in blood flow through anemometric principle.
Sensor Development

- **SIMULATION ANALYSIS (using COMSOL 4.1):**
  - Heater Material Selection,
  - Heater design,
  - Substrate Selection,
  - CFD Analysis: Velocity and Temperature distribution near the sensor and catheter tip with catheter insertion into the blood stream.
    - Steady state analysis
    - Transient analysis
Heater Selection & Design

HEATER SELECTION:
- Nichrome was chosen as the heater material due to very high TCR value.
- High stability over a wide range of operating temperature.

HEATER DESIGN:
- Uniform Heat distribution (Fig. E).
- Heater length: ~ 9 mm to mount around a catheter of diameter 3 mm.
- Resistance value: ~ 2 kΩ
**Substrate Selection**

*Substrate Area: 1cm x 1cm x 1mm; ΔT~ 6K; Ambient temperature = 300 K; R = 2.2 kΩ*

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Max. Heater Temp (K)</th>
<th>Voltage Input (V)</th>
<th>Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂/Si -Nichrome</td>
<td>305.9K</td>
<td>22</td>
<td>217.8</td>
</tr>
<tr>
<td>Glass -Nichrome</td>
<td>306.1K</td>
<td>9</td>
<td>36.9</td>
</tr>
<tr>
<td>PDMS -Nichrome</td>
<td>305.85K</td>
<td>4.2</td>
<td>7.98</td>
</tr>
</tbody>
</table>

**SUBSTRATE SELECTION:**

PDMS was selected over SiO₂ or glass as substrate for Nichrome heater due to:

- Less power requirement to attain similar temperature increment due to low thermal conductivity of PDMS.
- Biocompatibility, flexibility and ease of fabrication.
### Simulated Heater

**Surface: Temperature (K)**

- **Nichrome heater**

### Fabricated Heater

**Thermocouple**

**Fabricated heater**

**Electric Probes**

**Nichrome heaters over SiO₂/Si substrate**

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<table>
<thead>
<tr>
<th></th>
<th>Simulated Results</th>
<th>Tested Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage i/p (V)</td>
<td>22 V</td>
<td>25 V</td>
</tr>
<tr>
<td>Temperature increment (ΔT)</td>
<td>ΔT = 6.3 K</td>
<td>ΔT = 6 K</td>
</tr>
<tr>
<td>Resistance Change (ΔR)</td>
<td>ΔR = 8.3 Ω</td>
<td>ΔR = 7 Ω</td>
</tr>
</tbody>
</table>

**Simulation Details:**

- **Substrate Area:** 1cm x 1cm x 1mm;
- **Ambient temperature:** 300 K;
- **Thickness:** 0.2 µm;
- **Physics:** Electric Currents, Shell (ecs), Heat Transfer 2 (ht2);
- **Linearized resistivity;**
- **Two way coupling:** Heat source → ecs.Qrsh
- **Temperature for current conservation:** ht/solid1

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**Fabricated Nichrome micro heaters over PDMS substrate**
Sensor Modeling

Blood Vessel length = 8 cm
Blood Vessel diameter = 2 cm
Catheter length = 4 cm
Catheter diameter = 3 mm
Sensor Position = 2.5 cm from catheter tip
PDMS substrate thickness = 100 µm
Nichrome Heater thickness = 0.2 µm
Blood velocity = 0.2 m/s (-x axis)

Physics =
- Electric Currents, Shell (ecs)
- Electric Potential
- Conjugate Heat Transfer (ht)
- Temperature
- Velocity

Two way coupling = Heat source → ecs.Qrsh
Temperature for current conservation → ht/solid1

Mesh = Free tetrahedral
Ambient temperature (body) = 310 K (37 °C)
Temperature increment = 5K
Steady State Analysis

**COMSOL Equation:** Heat Transfer in Fluids solves the following equation for temperature, $T$

$$C_p \frac{\partial T}{\partial t} - \nabla \cdot (k \Delta T) + \rho C_p U \Delta T = Q$$

- $\rho$ is the density,
- $C_p$ is the heat capacity,
- $k$ is the thermal conductivity,
- $U$ is the fluid velocity and
- $Q$ is the heat source (or sink)

**Temperature distribution** = 315 K over the heater surface.
Meanderline heater structure with varying edges (25 µm & 40 µm) having a uniform temperature distribution.
Steady State Analysis

Electrical Potential distribution
I/p voltage req. = 12.8 V
Power req. = 60 mW
ΔT = 5K

Velocity distribution
= across blood vessel cross section with catheter

Velocity vectors
Transient Analysis

Blood velocity = 0.2 m/s (-x axis)

Physics =
- Electric Currents, Shell (ecs)
- Electric Potential
- Conjugate Heat Transfer (cht)
- Temperature
- Velocity

Two way coupling = Heat source → ecs.Qrsh
Temperature for current conservation → ht/solid1

Mesh = Free tetrahedral
Ambient temperature = 310 K (37 °C) [Body temperature]
Temperature increment = 5K

Study (Time dependent):
Range = (0, 0.05, 4)
Time stepping method = Generalized alpha
Remaining conditions = default settings
Transient analysis of temperature profile showing a rise time of 0.2 sec to increase the heater temperature by 5 K.
Temperature settles to normal body temperature of 310 K within about 100 µm above the heater surface.
Velocity profile

Blood Vessel

Catheter

Blood Flow direction

Velocity settling time = 0.4 sec
Conclusion and Future scope

Conclusion

- **Meanderline heater structure** with varying edges (25 µm & 40 µm) was chosen as the final heater design having a uniform temperature distribution.
- **Nichrome** was chosen as the sensing element due to its high TCR and high stability.
- **PDMS** was chosen as the substrate material due to its low thermal conductivity and flexible and biocompatible nature.
- Simulated test heater results were verified with a similar fabricated heater.
- Steady state analysis was performed for the sensor wrapped around the catheter:
  - \( 12.8 \text{ V for } \Delta T = 5\text{K} \ (315\text{K}) \)
- Transient analysis was performed:
  - \( Temperature \ \text{rise time} = 0.2 \text{ sec} \)
  - \( Velocity \ \text{settling time} = 0.4 \text{ sec} \)

Future scope

- Simulation of the sensor at varying positions over the catheter surface.
- Simulation of the sensor/catheter assembly near the wall of the blood vessel.
- Simulation of velocity/temp profile with pulsatile blood velocity in presence of catheter.
- Simulation of velocity/temp profile near a stenosis with/without the catheter.
- Simulation of multi hot wire anemometer assembly with multiple sensors over the catheter.
References & Acknowledgement

References:


Acknowledgement:

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