Simulation of MEMS Based Flexible Flow Sensor for Biomedical Application

Debashis Maji[*,1], Ravi Shankar Vunnam[2], C. P. Ravikumar[3] and Soumen Das[1]

[1]School of Medical Science and Technology, Indian Institute of Technology, Kharagpur-721302
[2]Department of Electrical Engineering, Indian Institute of Technology, Kharagpur-721302
[3]Texas Instruments (India) Pvt. Ltd., Bangalore, India

[*] **email:** ece.debashis@gmail.com

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Presentation Overview

- **Aim**
- **Hot-wire Anemometry Principle**
- **Literature Survey**
- **Sensor Development**
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    - Sensor Geometry
- **Steady State Analysis**
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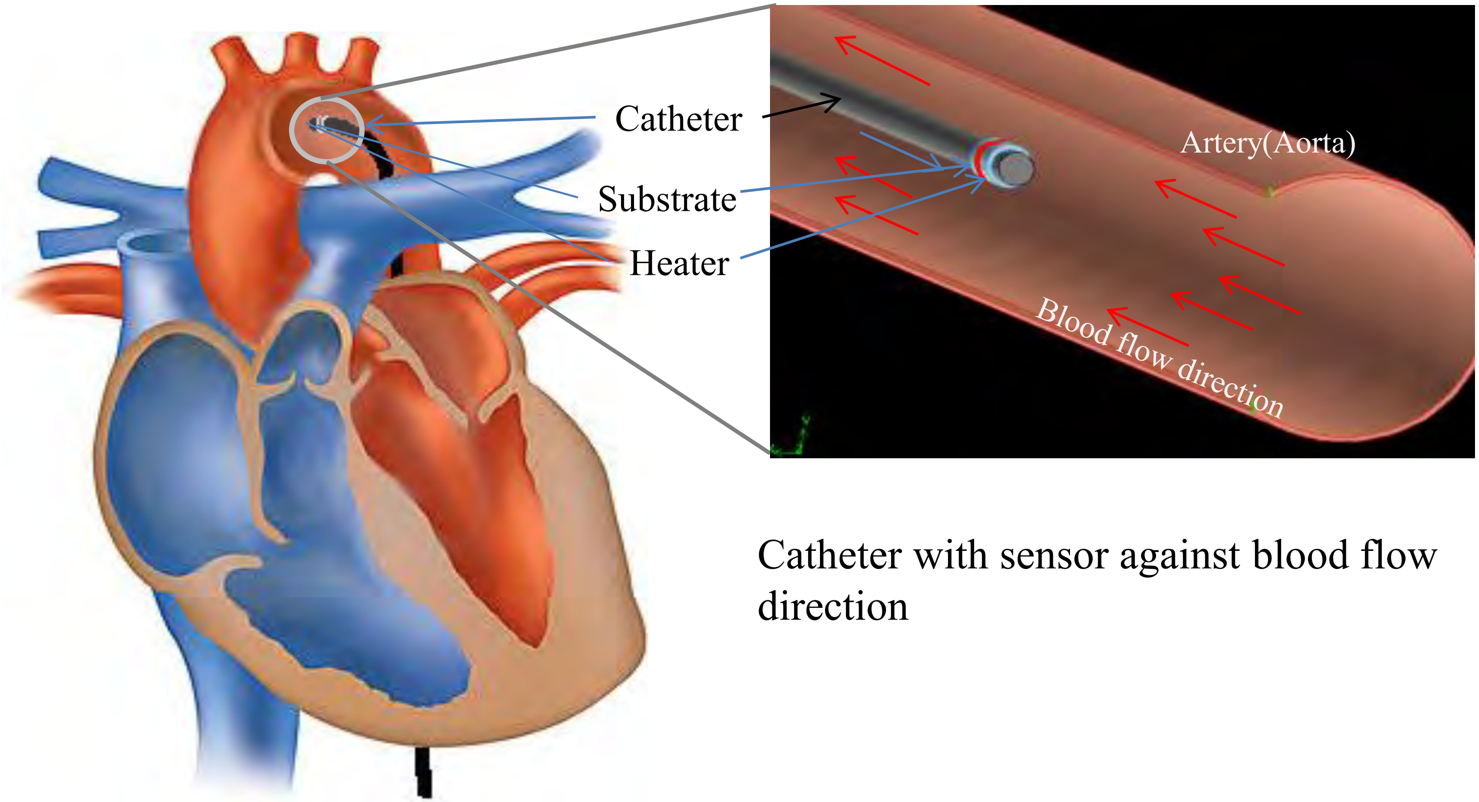
    - Pressure profile
- **Conclusion and Future scope**
- **References & Acknowledgement**

Aim

Development of MEMS Based Flexible Flow Sensor for Health Care Monitoring



Catheter with sensor against blood flow direction

Catheter Pathway through Aorta

SENSOR SETUP

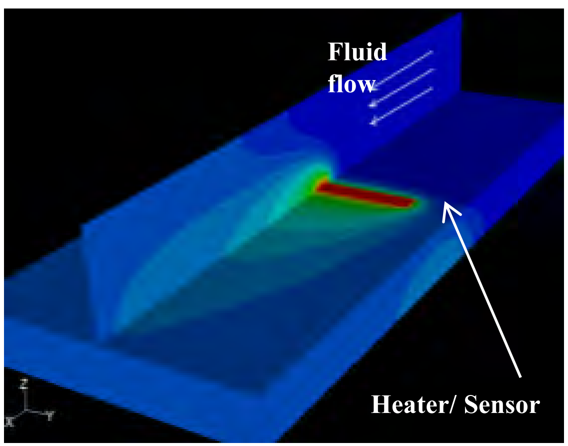
Hot-wire Anemometry Principle

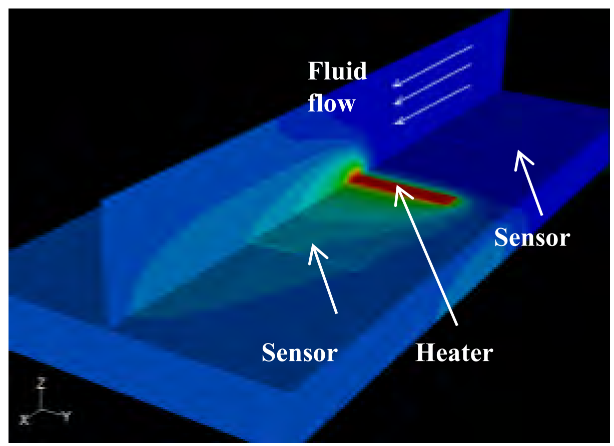
Principle (*Hot-wire Anemometer*):

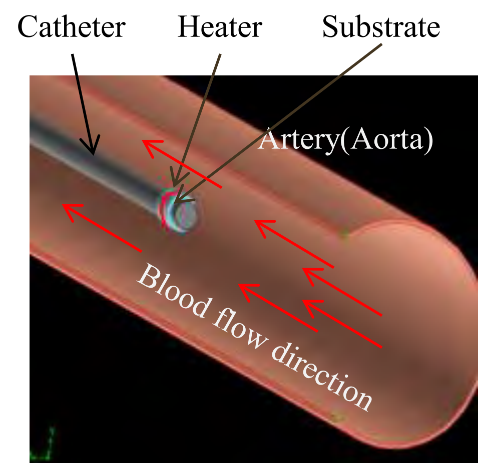
Fluid velocity is determined by the amount of heat dissipated in the fluid from the electrically heated sensing element exposed in the fluid medium.

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

$$I^2R_w = h.A_w(T_w - T_f)$$

I : input current
R_w : Resistance of the wire
h : Heat transfer coefficient of the wire
A_w : Projected wire surface area
T_w & T_f : temperatures of the wire and fluid respectively

Wire resistance R_w at temperature T_w is given by:

$$R_w = R_{\mathrm{Re}f}[1 + \alpha(T_w - T_{\mathrm{Re}f})]$$

T_{Ref} : Reference temperature
R_{Ref} : Reference resistance of wire
α : Temperature coefficient of resistance of wire's material at T_{ref}

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

$$h = a + b.v_f^{\,c}$$

a, b, and c are coefficients obtained from calibration-
a :combination of effective area of thermal element, stream wise length, heat capacity, thermal conductivity and viscosity of the fluid.
b :conductance heat loss to the surface.
c :1/3
v_f :Fluid velocity

Hence, fluid velocity is given by:

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

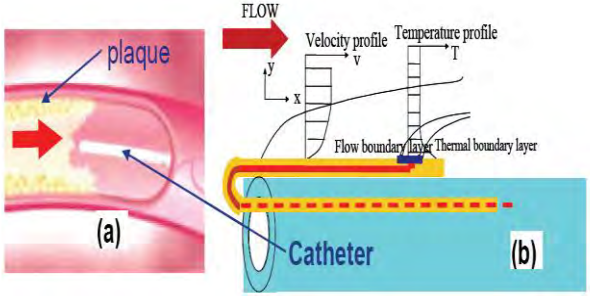
➡ $I^2 \; \alpha \; v_f^{\,1/3}$

Literature Survey

- **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.

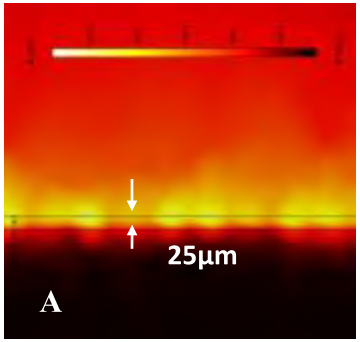
Sensor Development

- ***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

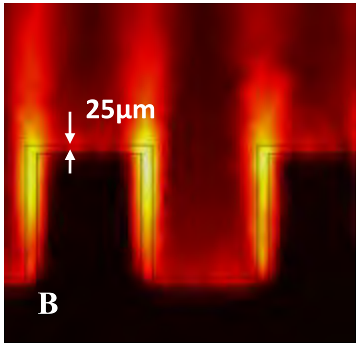
Heater Selection & Design

HEATER SELECTION:

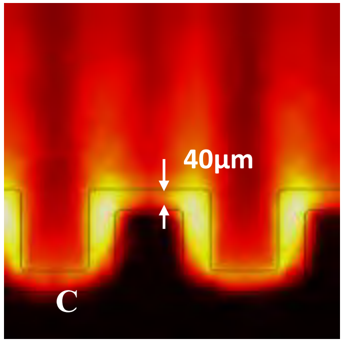
- Nichrome was chosen as the heater material due to very high TCR value.
- High stability over a wide range of operating temperature.



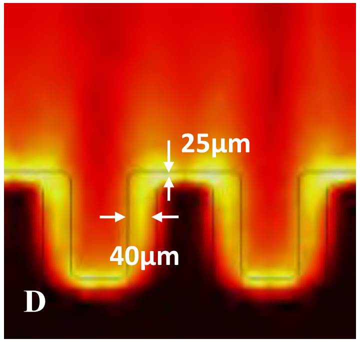
Straight Heater (width= 25µm)



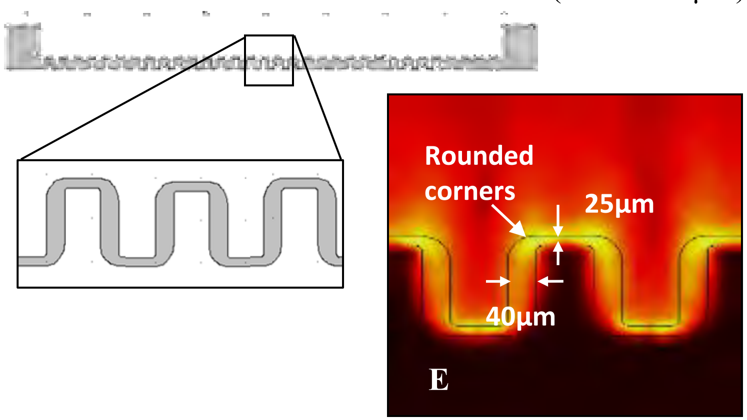
Meanderline Heater structure (width= 25µm)



Meanderline Heater structure (width= 40µm)



Meanderline Heater structure with varying width (width= 25 & 40µm)

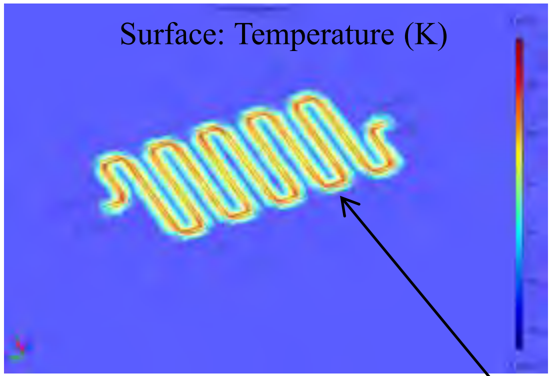


Meanderline Heater structure with rounded corners (width= 25 & 40µm)

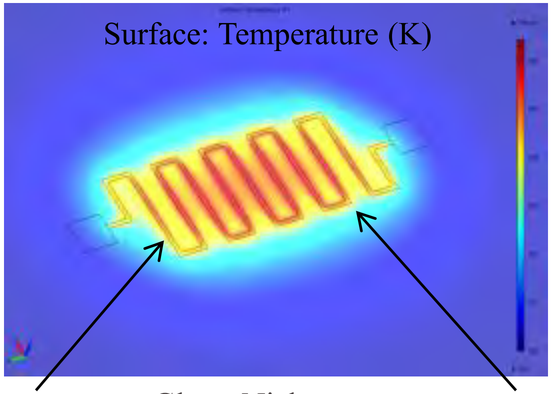
HEATER DESIGN:

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

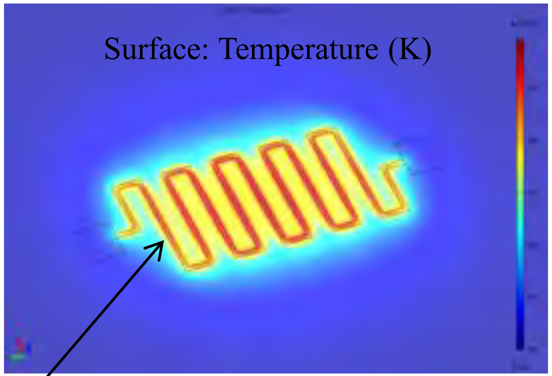
Substrate Selection



SiO_2/Si -Nichrome



Glass -Nichrome



PDMS -Nichrome

Nichrome heater

Nichrome heater

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

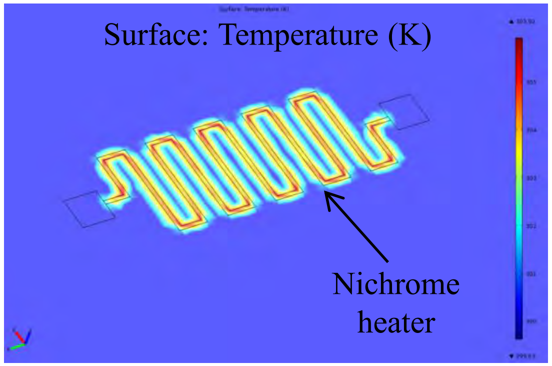
SiO_2/Si -Nichrome	Glass-Nichrome	PDMS-Nichrome
Max. Heater Temp- 305.9K	Max. Heater Temp- 306.1K	Max. Heater Temp- 305.85K
Voltage i/p- 22 V	Voltage i/p– 9 V	Voltage i/p– 4.2 V
Power – 217.8 mW	Power – 36.9 mW	Power – 7.98 mW

SUBSTRATE SELECTION:

PDMS was selected over SiO_2 or glass as substrate for Nichrome heater due to:

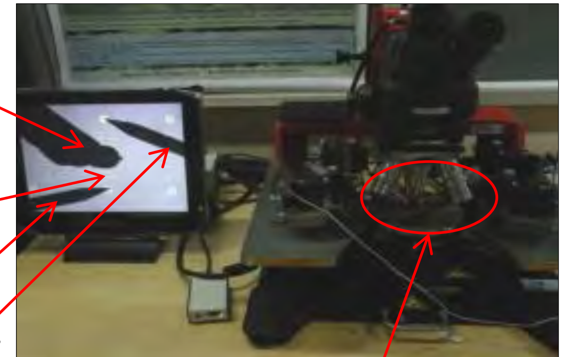
- Less power requirement to attain similar temperature increment due to low thermal conductivity of PDMS.
- Biocompatibility, flexibility and ease of fabrication.

Simulated Heater



SiO_2/Si -Nichrome

Fabricated Heater

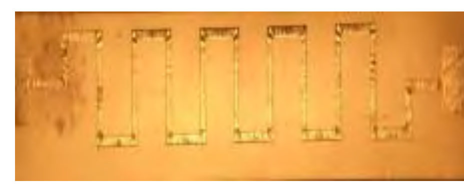


Nichrome heaters over SiO_2/Si substrate

	Simulated Results	Tested Results
Voltage i/p (V)	22 V	25 V
Temperature increment (ΔT)	ΔT = 6.3 K	ΔT = 6 K
Resistance Change (ΔR)	ΔR = 8.3 Ω	ΔR = 7 Ω

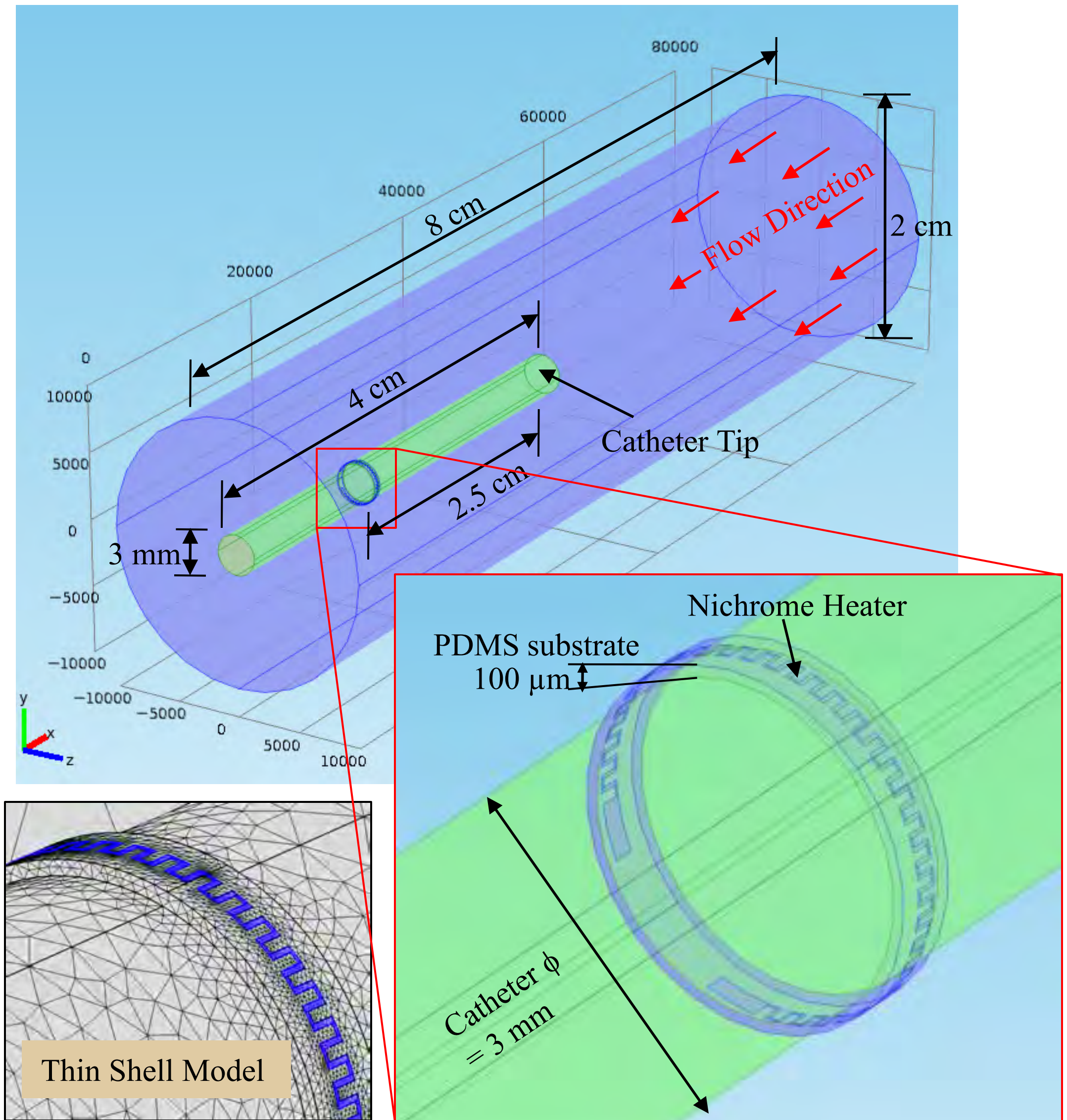
Simulation Details:

- 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



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 *(nitf)*
  - → Temperature
  - → Velocity

} Linearized resistivity

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

Mesh = Free tetrahedral

Ambient temperature (body)= 310 K (37 °C)

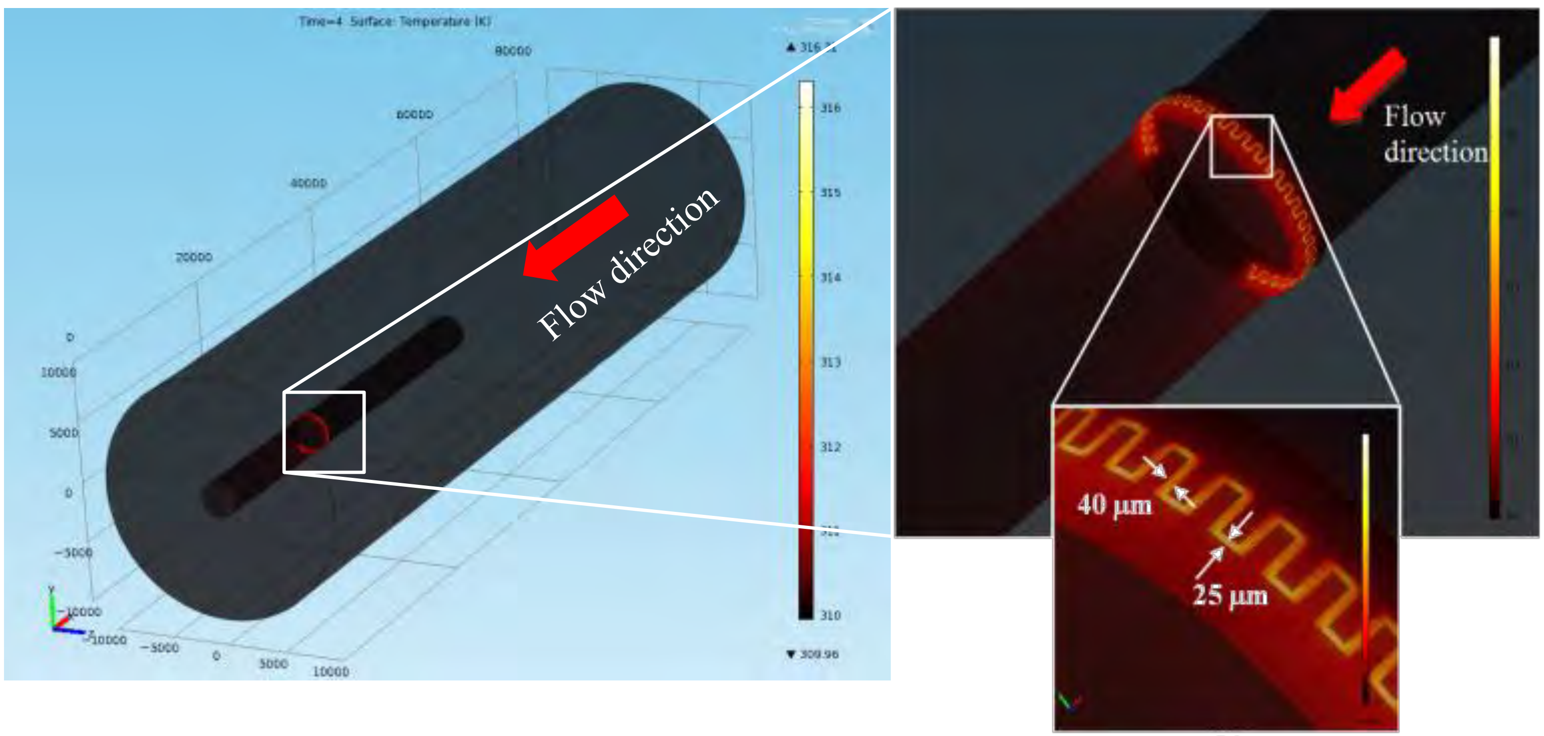
Temperature increment = 5K

Steady State Analysis

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

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

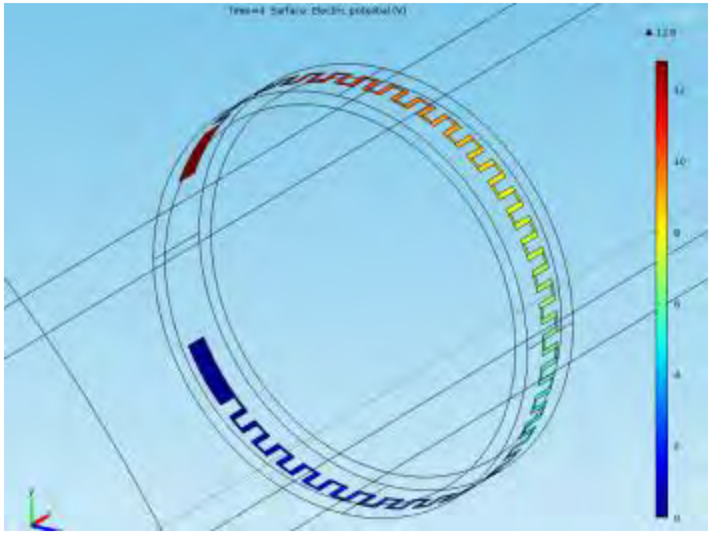
ρ is the density,
C_p is the heat capacity,
k is the thermal conductivity,
U is the fluid velocity and
Q is the heat source (or sink)



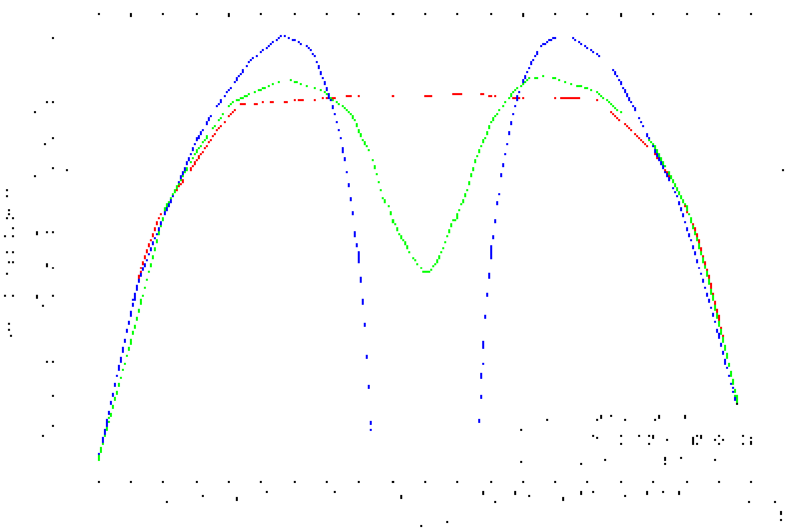
Temperature distribution = 315 K over the heater surface.

Meanderline heater structure with varying edges (25 µm & 40 µm) having a uniform temperature distribution.

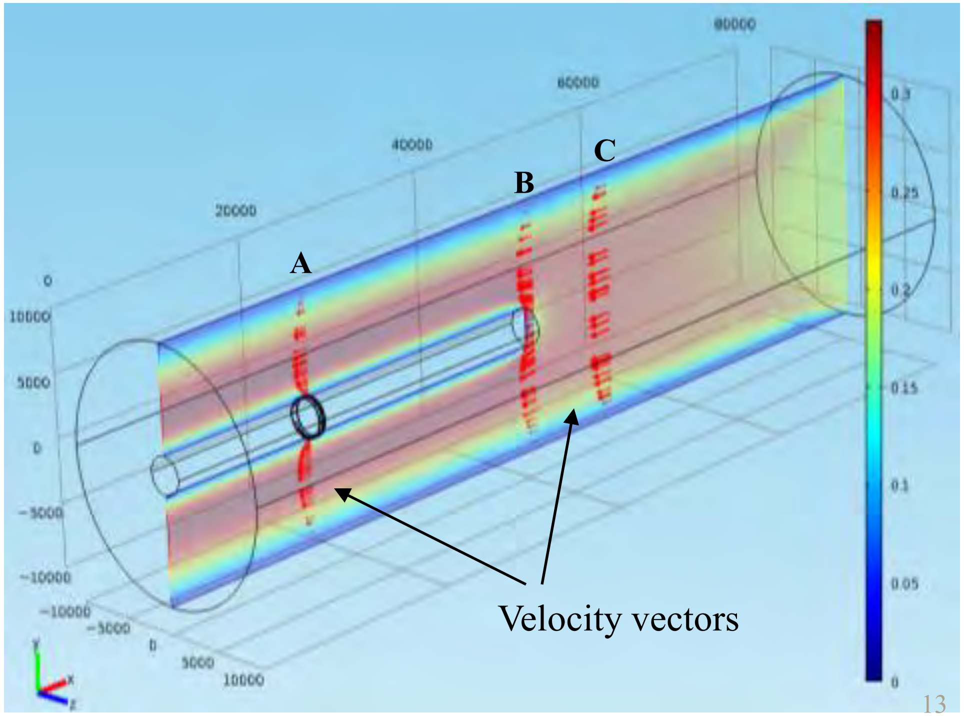
Steady State Analysis



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

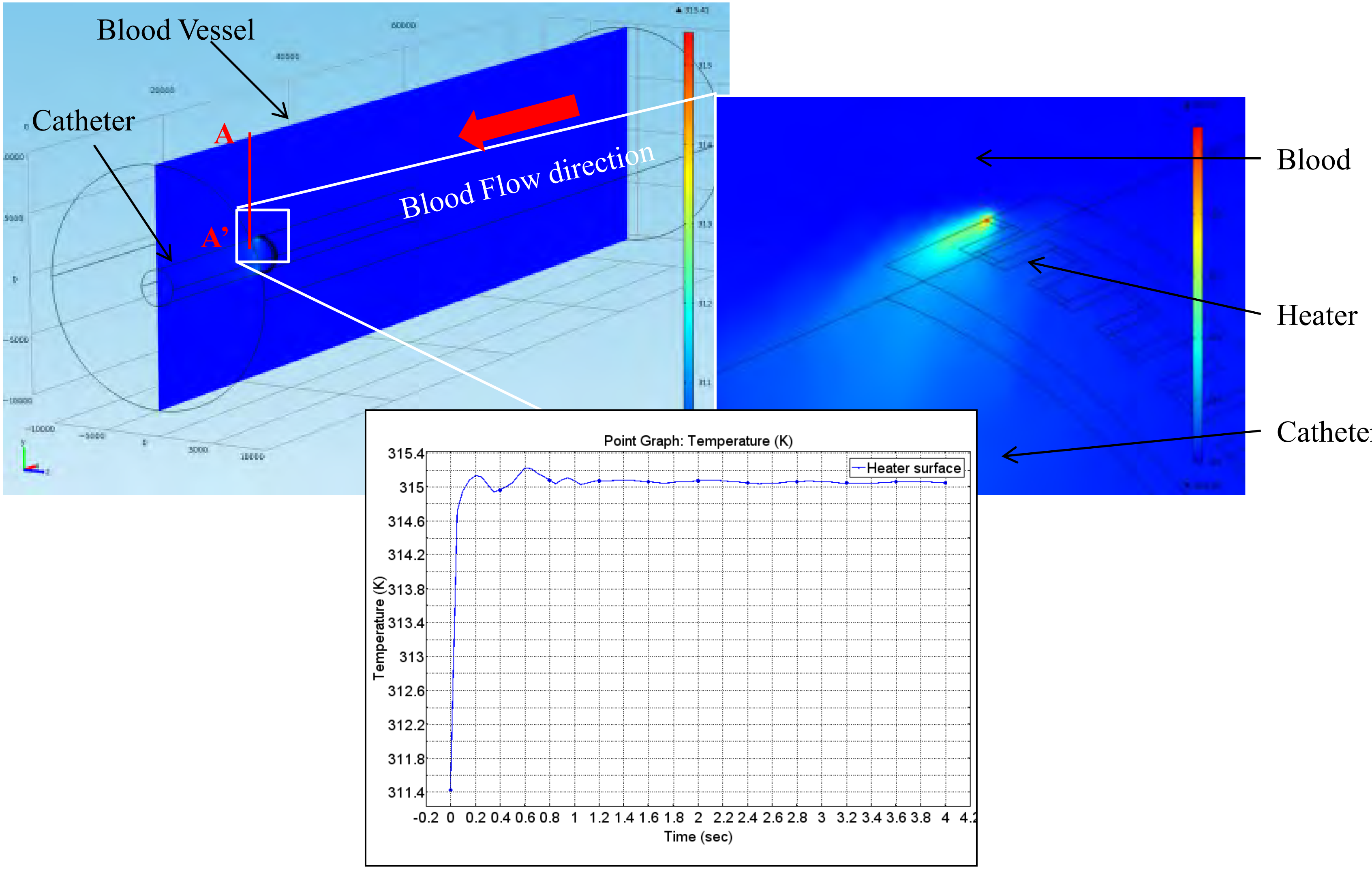


Transient Analysis

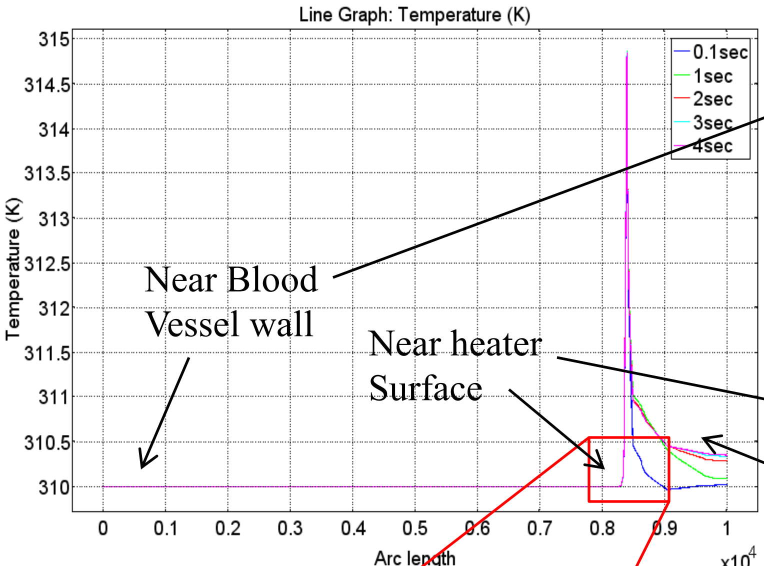
Simulation Details:

- Blood velocity = 0.2 m/s (-x axis)
- Physics =
  - Electric Currents, Shell *(ecs)*
    - Electric Potential
  - Conjugate Heat Transfer *(nitf)*
    - Temperature
    - Velocity
  - Linearized resistivity
- 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

Temperature profile



Transient analysis of temperature profile showing a rise time of 0.2 sec to increase the heater temperature by 5 K



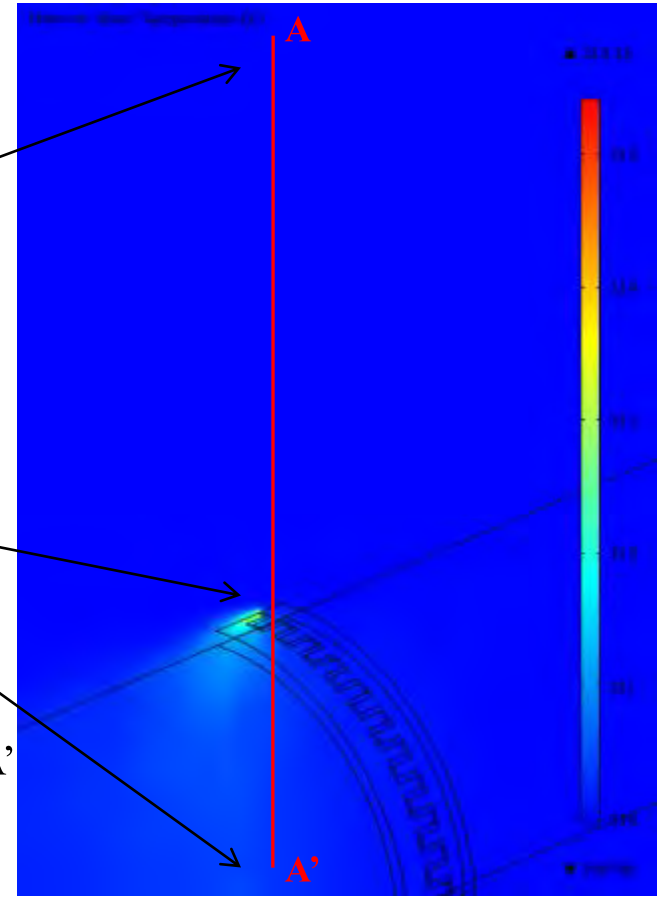
Near Blood Vessel wall

Near heater Surface

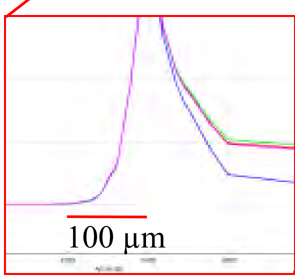
Inside the catheter

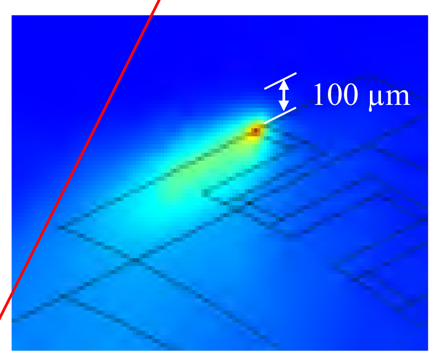
A A'

Variation of temperature profile across the blood vessel A-A'



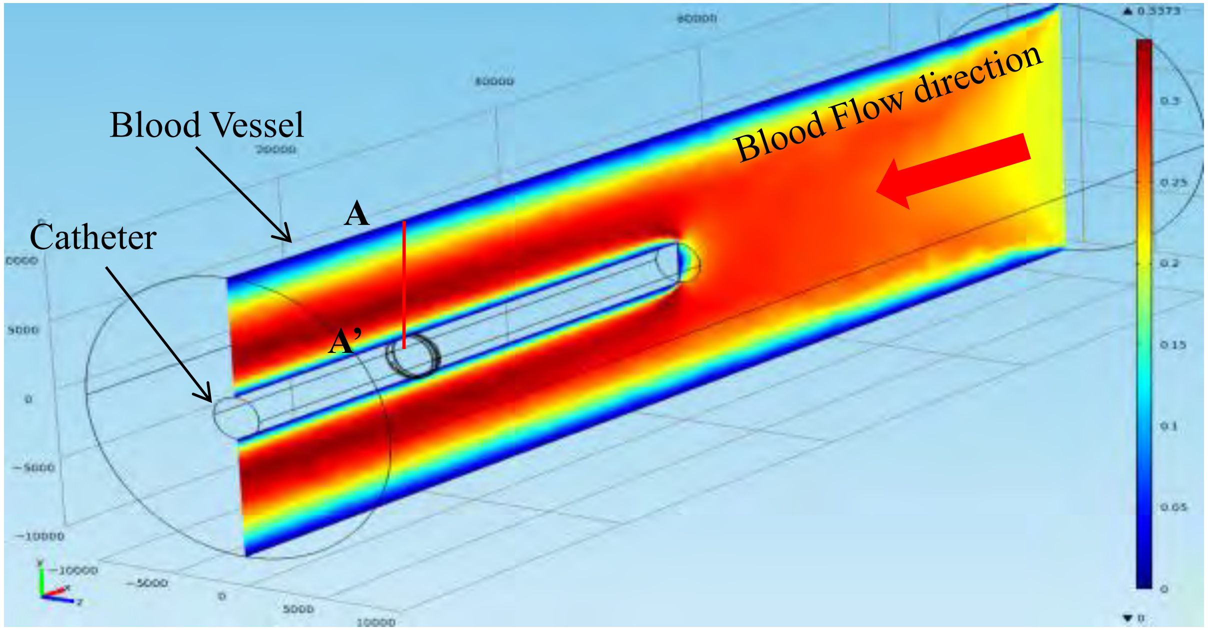
310 K

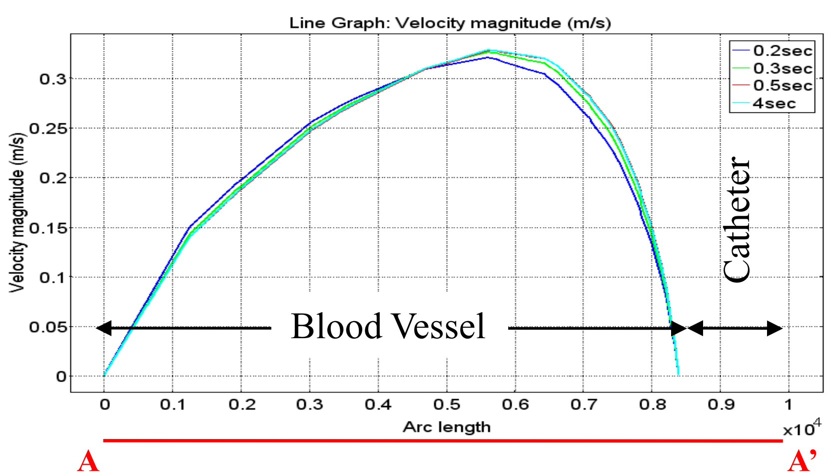


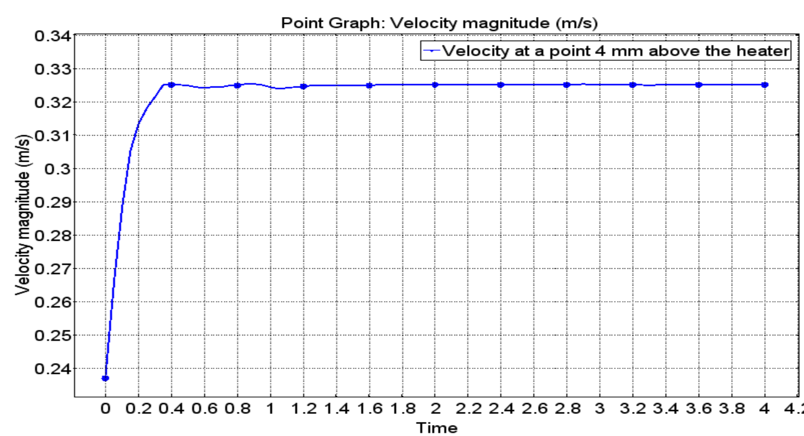


Temperature settles to normal body temperature of 310 K within about 100 μm above the heater surface.

Velocity profile







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 V for $\Delta T = 5K$ (315K)
- **Transient analysis** was performed:
  - *Temperature rise time* = 0.2 sec
  - *Velocity settling time* = 0.4 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

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Thank you