The PressureWire as a flow meter

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| 1 | **Introduction**                                      | 3 |
|   | 1.1 Assessment of coronary and microvascular disease | 3 |
|   | 1.2 The PressureWire                                  | 3 |
|   | 1.3 Hot-wire anemometry                               | 4 |
|   | 1.4 Combined pressure and flow measurement            | 7 |
| 2 | **Method 1: Chip characteristics**                   | 8 |
|   | 2.1 Introduction                                     | 8 |
|   | 2.2 Method                                           | 8 |
|   | 2.3 Results                                          | 9 |
|   | 2.4 Discussion                                       | 9 |
|   | 2.5 Conclusion                                       | 9 |
| 3 | **Method 2: Heat loss**                              | 11 |
|   | 3.1 Introduction                                     | 11 |
|   | 3.2 Method                                           | 11 |
|   | 3.3 Results                                          | 14 |
|   | 3.4 Discussion                                       | 15 |
|   | 3.5 Conclusion                                       | 16 |
| 4 | **Method 3: PressureWire in a CTA application**       | 17 |
|   | 4.1 Introduction                                     | 17 |
|   | 4.2 The CTA circuit and experimental set-up          | 17 |
|   | 4.3 Method                                           | 19 |
|   | 4.4 Results                                          | 20 |
|   | 4.5 Discussion                                       | 27 |
|   | 4.6 Conclusion                                       | 28 |
| 5 | **Method 4: Chip position and ambient temperature**  | 29 |
|   | 5.1 Introduction                                     | 29 |
|   | 5.2 Method                                           | 29 |
|   | 5.3 Results                                          | 29 |
|   | 5.4 Discussion                                       | 31 |
|   | 5.5 Conclusion                                       | 31 |
| 6 | **Discussion**                                       | 32 |
| 7 | **Conclusion**                                       | 33 |
| 8 | **References**                                       | 34 |
|   | Appendix A                                           | 35 |
|   | Appendix B1                                          | 36 |
|   | Appendix B2                                          | 49 |
Chapter 1

Introduction

1.1 Assessment of coronary and microvascular disease

Cardiovascular dysfunction may be caused not only by stenosis in the coronary arteries but also by disease of the capillaries; the microvasculature. To evaluate cardiovascular function during coronary catheterization one needs measurements of relevant parameters like flow rate and pressure in addition to the information obtained by angiography [1]. Two important indices to quantify the physiological significance of coronary stenosis and microvascular disease are CFR (Coronary Flow Reserve) and FFR (Fractional Flow Reserve). CFR is based on measurements of resting and hyperaemic flow to determine the ability of the coronary system to increase flow during increased demand of oxygen and corresponding minimization of vascular resistance. FFR is based on pressure measurement proximal and distal of a stenosis at hyperaemic flow and indicates the functional significance of a stenosis [2]. Simultaneous measurement of the CFR and FFR during coronary catheterization by one single wire would improve qualification of the contribution of epicardial stenosis and microvascular dysfunction to the extent of cardiovascular ischemia. CFR and FFR both low indicate a functionally significant stenosis whereas low CFR in combination with high FFR indicates microvascular disease [1].

Currently pressure and flow rate can be measured by means of separate wires introduced into the arterial system through the groin [1]. The measurement of flow is based on Doppler ultrasound measurement where actually flow velocity is measured and additional information on the geometry of the vessel is needed for the assessment of the flow rate [1]. Pressure wires use the principle of membrane deformation measured by a strain gauge [1]. To determine the CFR and FFR simultaneously the pressure and the flow rate must be measured simultaneously. For flow measurement with a pressure wire the temperature-sensitivity of the strain gauge (resistor) might be used. The aim of the project is:

Evaluate the possibility to use the PressureWire sensor (Radi Medical Systems, Uppsala, Sweden) as a flow sensor.

The temperature-sensitivity of the PressureWire sensor might be used in flow rate measurements. The change in sensor temperature is assumed to be related to the flow rate.

1.2 The PressureWire

Nowadays the Radi PressureWire is used in clinical environment to measure pressure in coronary arteries and determine FFR. The PressureWire has a working length of 175 cm and a diameter of 0.36 mm. The PressureWire can be attached to the Radi Analyzer (this interface for controlling and processing the signal, is not used in this report) by a connector, the first part of the PressureWire. The sensor is located at 30 mm from its tip (figure 1.1).
The sensor consists of two resistances on a chip: passive resistance ($R_p$) and active resistance ($R_a$). Both resistances are strain gauges. But only $R_a$ can be used to measure the pressure, because it is located on a membrane that deforms depending on the local pressure. $R_p$ is used to compensate the pressure signal for ambient temperature changes. It is assumed that $R_p$ and $R_a$ have similar sensitivity to temperature. In this report the $R_p$ will be used to measure the flow rate. Three cables inside the wire connect the resistances (figure 1.2).

The chip is glued onto a plate at a small angle $\theta$. A metal casing is placed around the plate, leaving the chip exposed to the fluid. The chip can be seen as the bottom of a small cavity, partly covered by silicon to protect the electrical connections [1] (figure 1.3).

1.3 **Hot-wire anemometry**

One way to measure the flow with the PressureWire is hot-wire anemometry. Hot-wire anemometry (HWA) is the most well known thermal anemometry measurement technique. The principle of HWA is that a resistance is heated up till the
temperature is above the ambient temperature. The heat transfer from the resistance to the ambient is a measure for the flow. The temperatures of the resistances on the chip of the PressureWire are change as a result of the flow (figure 1.4).

Consequently any change in the fluid flow condition that affects the heat transfer from the heated element (the resistances on the chip) can be studied with HWA [3].

Two types of thermal (hot-wire) anemometers are commonly used: constant temperature anemometry (CTA) and constant current anemometry (CCA). In the CTA mode the temperature of the resistance is constant. The electrical power, needed to keep the temperature constant and hence the resistance itself, is a measure for the heat transferred to the fluid and flow rate along the resistance. In the CCA mode the current through the resistance is constant. The temperature change of the resistance is a measure for the heat transferred to the fluid and flow rate along the resistance.

*In this report the feasibility of the use of the PressureWire in a CTA application is investigated. The passive resistance of the PressureWire is used.*

### 1.3.1 Constant temperature anemometry

The basic circuit for a CTA is shown on figure 1.5. \( R_p \) is incorporated in a Wheatstone bridge. \( R_c \) represents the cables resistance of the cables inside the PressureWire. The imbalance in the bridge \((V_1 - V_2)\) is measured using an operational amplifier. The operational amplifier outputs whatever voltage is necessary to bring the bridge back into balance. In a CTA the resistors \( R_1, R_2, \) and \( R_{\text{control}} \) are very stable and are assumed to be constant. \( R_p \) and \( R_c \) are temperature dependent according to:

\[
R(T) = R_{\text{ref}} \left( 1 + \alpha_{\text{ref}} (T - T_{\text{ref}}) \right)
\]

\( T \) = Temperature of the resistor [°C]
\( T_{\text{ref}} \) = Begin temperature [°C]
\( R \) = Resistance of the resistor at temperature \( T \) [Ω]
\( R_{\text{ref}} \) = Resistance of the resistor at \( T_{\text{ref}} \) [Ω]
\( \alpha_{\text{ref}} \) = Temperature coefficient at \( T_{\text{ref}} \) [°C\(^{-1}\)] \((\alpha_{\text{ref}} > 0)\)

The imbalance in the bridge is a result of ambient temperature changes influencing \( R_p \) and \( R_c \), and heating of \( R_p \). We assume that the internal heating of \( R_p \) does not lead to similar increase in cable temperature because of the limited power dissipated in the cable. So the cable resistance will only change when the ambient temperature changes.
Suppose that, starting from the case where the bridge is balanced at a given flow rate \(((R_p + 2R_c)/R_{control} = R_2/R_1 \text{ and } V_1 = V_2)\), the flow rate increase. This will take heat away from \(R_p\). The temperature of the \(R_p\) (and hence its resistance) will decrease causing the bridge to become unbalanced \(((R_p + 2R_c)/R_{control} < R_2/R_1 \text{ and } V_1 < V_2)\). The \(R_c\) does not change because the ambient temperature does not change. The operational amplifier senses this imbalance in the bridge and increases its output voltage \((V_{amp})\) and thus makes more power available for the \(R_p\) to dissipate to maintain its temperature constant. So the bridge become back into balance. Changing the value of \(R_{control}\) controls the operating temperature of the wire.

![Figure 1.5: Schematic of CTA circuit](image)

1.3.2 Equation governing hot-wire anemometry

HWA is based on the convective heat transfer from a heated wire or film placed in a fluid flow. Assume that the \(R_p\), heated by an electrical current input, is in thermal equilibrium with its environment. The electrical power supplied to the \(R_p\) is equal to the heat transfer \(\phi\) dissipated in the flow.

\[
\phi_e = R_p I_p^2 \quad \text{or} \quad \phi = \frac{V^2}{R_p}
\]  

(1.2)

The heat transfer is also equal to the temperature difference between the temperature of the heated wire \((T_w)\) and the temperature of the ambient fluid \((T_a)\) multiplied by the wire surface area \((A_w)\) and a heat transfer coefficient \((h)\). This is the convective heat transfer:

\[
\phi_h = h \cdot \pi d l (T_w - T_a) = h \cdot A_w (T_w - T_a)
\]  

(1.3)

d = diameter of the wire
l = length of the wire
In HWA we assume force-convective heat transfer. In this case the electrical power supplied to $R_p$ is equal to the power lost to convective heat transfer ($\phi_c = \phi_h$). (1.2) and (1.3) can be combined to find the relation between the excitation voltage and the heat transfer coefficient $h$.

$$\frac{V_p^2}{R_p} = h \cdot A_w(T_w - T_a)$$

(1.4)

The flow dependency of (1.4) is the heat transfer coefficient ($h$). The heat transfer coefficient is a function of flow velocity ($U$) according to King’s law [9].

$$h = K_0 + K_1 U^n$$

(1.5)

In equation 1.5 $K_0$ and $K_1$ are constants. The exponent $n$ depends on the geometry of the PressureWire sensor. The excitation voltage ($V_p$) can be related to the flow velocity by combining (1.4) and (1.5).

$$V_p^2 = A + BU^n$$

(1.6)

In (1.6) the parameter $A$ and $B$ are velocity-independent constants.

### 1.4 Combined pressure and flow measurement

If the PressureWire can be correctly calibrated and the calibration parameters ($A$, $B$ and $n$) in blood can be found, the wire may possibly be used for simultaneous pressure and flow rate measurement. This will enable direct calculation of the resistance of the myovascular bed (arteries and capillaries embedded in muscle) which in turn can be used as an index of microvascular disease. FFR and this microvascular resistance will describe the epicardial and microvascular compartment, respectively, and the contribution of the epicardial stenosis and microvascular dysfunction to the extent inducible ischemia.

*The aim of the training is to investigate the feasibility of the use of the PressureWire in a CTA application.*

To use the PressureWire as a hot-wire it is necessary to know how the sensor is heated up by itself and to what extent can it be heated by increasing the voltage across it. This is the subject of chapter 2. In chapter 3 an experiment is done to investigate which part of the heat is lost by conduction and which part by convection. The calibration parameters are examined at varying flow rate in a tube with a diameter resembling that of a coronary artery. In the last chapter the influence of the chip position in the tube and changes in the ambient temperature on the calibration parameters are investigated. In conclusion the experimental results will be evaluated to verify the feasibility of the use of the current PressureWire in a CTA application.
Chapter 2

Method 1: Chip characteristics

2.1 Introduction

The sensor of hot-wire anemometer consists of a variable electrical resistance. This resistor can be heated up by itself by increasing the electrical voltage across it. The resistance value of the resistor increases as a consequence of the increased temperature.

To use \( R_p \) as a hot-wire it is necessary to know how the resistance of \( R_p \) changes by increasing the voltage across it. In other words how \( R_p \) is heated up by itself and to what extent it can be heated by increasing the voltage across it.

2.2 Method

To investigate how \( R_p \) is heated up by itself \( R_p \) is excited by increasing voltage \( (V) \) from 0.5 V to 10 V with steps of 0.5 V. The current \( (I) \) through \( R_p \) and the voltage across it are measured (Keithley multimeter) (figure 2.1). The resistance is calculated with Ohm’s law:

\[
R = \frac{V}{I}
\]  

(2.1)

As mentioned in chapter 1 the internal heating of \( R_p \) in our experiment does not lead to similar increase in cable temperature because of the limited power dissipated in the cable. So the cable resistance will not change during the experiment, because ambient temperature is kept constant. During this experiment the cables are not taken into account. This experiment is done in air and in water. The temperature of the air is not measured and is around 20 \( ^\circ \)C. The temperature of the water is 37 \( ^\circ \)C and is kept constant with two heating elements in a water bath (Grant) (figure 2.2). There is also some flow circulation in the water bath to maintain a homogeneous temperature.

![Figure 2.1: Circuit for resistance measurement. In this circuit \( R_p \) and \( R_a \) are the passive and active resistance of the PressureWire, respectively. \( R_a \) is not included in the circuit: is not excited and no current is flowing through it.](image-url)
If $R_p$ is an ideal resistor and not self-heating the resistance value will not be change when the voltage across it increase and I versus V plot will be linear.

### 2.3 Results

The dots in figure 2.3 are the measurement points in air and water. The black line represents an ideal resistor. For both water and air the measurements point start to deviate from the ideal resistor when the excitation voltage increases above 2V. In figure 2.4 the resistance difference ($\Delta R$) is plotted against the supplied voltage. $R_{ref}$ is taken at the lowest voltage, so $R_p$ will have its initial resistance at ambient temperature. To get a good fit through the data points a second order polynomial is chosen.

### 2.4 Discussion

In this experiment the cables inside the PressureWire with resistance $R_c$ can not be neglected. Because the voltage drop across the cable ($V_c$) will increase if the excitation voltage increases, because the current through it increases ($V_c = IR_c$). So the voltage drop across $R_p$ is:

$$V_p = V - 2R_c I = V - V_c$$

(2.2)

instead of the measured voltage (V) in figure 2.1. This means that the resistance difference in figure 2.4 is lower and thus the temperature difference is lower. In the next chapter the cables inside the PressureWire are taken in account.

### 2.5 Conclusion

From figure 2.3 and 2.4 we see that the resistance is increased if the voltage is increased. This means that the $R_p$ is heated up by itself. So it is possible to use the $R_p$ as a hot-wire. From figure 2.4 we see that resistance in air at 20 °C increase more than in water at 37 °C, this means that in air the resistor heated up more than in water. A
reason for this is that the conductivity in water is better than in air; more heat is
directly diffused into the water than into air.

Figure 2.3: I versus V of $R_p$ in air and water (dots). The line represents an ideal resistor.

Figure 2.4: $\Delta R$ versus V. $R_{ref}$ is the resistance at the lowest voltage. It is fitted with a second
der order polynomial.
Chapter 3

Method 2: Heat loss

3.1 Introduction
As seen in chapter 2, $R_p$ is heated up by itself. But how much of this heat goes to the chip and how much goes to the fluid? In other words, how much of the energy is lost by conduction and how much by convection? In hot wire anemometry we assume dominant convective heat transfer (equation 1.3), so to use $R_p$ in a HWA application the main part of the heat must go to the fluid by convection.

3.2 Method
The chip temperature might be monitored by the active resistance of the PressureWire ($R_a$). For this $R_a$ is supplied with a low constant current, so it will not heat up by itself. Fluke Multimeter delivers the constant current. The change in resistance of $R_a$ is now caused by the change in chip temperature, as a result of $R_p$, if the fluid or air temperature is constant (figure 3.1).

![Diagram](image)

**Figure 3.1:** By increasing the voltage across $R_p$, the resistance itself, and its environment (the chip) are heated up. The resistance of $R_a$ may monitor the change in chip temperature.

$R_p$ is heated up by exciting it with an increasing voltage ($V$) from 0.5 V to 10 V with steps of 0.5 V. The current ($I_p$) through $R_p$ and the voltage across it ($V$) are measured (Keithley multimeter). $R_a$ is excited with a constant current ($I_a$) and the voltage drop across it ($V_{drop,a}$) is measured (Keithley multimeter) (figure 3.2). This experiment is done in air at around 20 °C and in water at 37 °C. The air temperature is not measured and for the water experiment the same experimental setup of chapter 2 (figure 2.2) is used with the extension of the excitation of $R_a$. To maintain a homogenous temperature there is some flow circulation in the water bath. This flow circulation has no cooling effect on the chip.
Figure 3.2: Circuit for chip temperature measurement.

\[ R_p \text{ is:} \]
\[ R_p = \frac{V - R_c I_p - R_c I_c}{I_p} = \frac{V_p}{I_p} \]  
(3.1)

And \( R_a \) is:

\[ R_a = \frac{V_{\text{drop}, a} - R_c I_a - R_c I_c}{I_a} = \frac{V_a}{I_a} \]  
(3.2)

with \( I_c \) is:

\[ I_c = I_a + I_p \]  
(3.3)

**Determination of \( R_c \)**

For the cables inside the PressureWire a constant resistance value are taken (\( R_c \)). The circuit in figure 3.3 can be used to measure \( R_c \). \( R_a \) is excited with a constant current (Fluke Multimeter). The voltage across the cable (\( V_{R_c} \)) can not measured directly, because it is only possible to measure at the points \( G_{\text{round}}, A_{\text{active}}, P_{\text{passive}} \). Instead the voltage between \( P_{\text{passive}} \) and \( G_{\text{round}} \) (\( V_q \)) is measured with a Keithley multimeter. The Keithley multimeter has high input impedance so that no current flowing through the \( R_p \). In this case \( V_q \approx V_{R_c} \). \( R_c \) is measured with about 80% of its length in a water bath at 37 \(^\circ\)C.
Figure 3.3: Circuit for measure the cable resistance ($R_c$)

$R_c$ is:

$$R_c = \frac{V_c}{I}$$  \hspace{1cm} (3.4)

$R_c$ has a resistance of 45.16 $\Omega$ at 37 °C. This value is taken for each of the three cables inside the PressureWire. In section 3.4 it will be shown that for the experiment in air at 20 °C the same value for $R_c$ can be used.

**Determination of the temperature coefficient of $R_a$ and $R_p$**

To calculate the temperature difference (1.1) is rewritten:

$$T_w - T_a = \frac{R_w - R_{\text{ambient}}}{R_w \cdot \alpha_a}$$ \hspace{1cm} (3.5)

- $T_w$ = Temperature of heated wire [°C]
- $T_a$ = Ambient temperature [°C]
- $R_w$ = Resistance of heated wire at $T_w$ [\Omega]
- $R_{\text{ambient}}$ = Resistance of wire at $T_a$ [\Omega]
- $\alpha_a$ = Temperature coefficient at $T_a$ [°C$^{-1}$]

To relate the resistance difference to the temperature difference the temperature coefficient ($\alpha$) in equations 3.5 has to be calculated. The temperature coefficient of $R_p$ and $R_a$ are determined with a constant low current (Fluke Multimeter) through them (So it will not heated up by itself) and measure the voltage across them at three different water temperatures. Only three measurement point are taken, because a linear relation between the temperature difference and the resistance difference is expected, see equation 3.5
3.3 Results

![Graph](image)

Figure 3.4: The resistance difference divide to the reference resistance versus the temperature difference. The slope of the red line and black line are the temperature coefficients at 25 °C of Ra and Rp, respectively.

The slopes of the lines in figure 3.4 are the temperature coefficients of the R_a and R_p at 25 °C. The temperature coefficients of the R_p and R_a at 25°C are $6,1 \cdot 10^{-4} \text{ °C}^{-1}$ and $6,4 \cdot 10^{-4} \text{ °C}^{-1}$, respectively.

The temperature coefficient at another temperature can be calculated with:

\[
\alpha_d = \frac{R_{25}}{R_d} \alpha_{25}
\]  

(3.6)

\(\alpha_d\) = Temperature coefficient at desired temperature  
\(\alpha_{25}\) = Temperature coefficient at 25 °C  
\(R_d\) = Resistance of R_p at desired temperature. This can be calculated with equation 1.1. With \(R_{ref} = R_{25}\), \(\alpha_{ref} = \alpha_{25}\) and \(T = \text{desired temperature}\).  
\(R_{25}\) = Resistance of R_p at 25 °C

From figure 3.5 and figure 3.6 it can be seen that both R_p and chip become warmer in air than in water. So the heat transfer in water is better than in air. In figure 3.5 it can be seen that R_p is about 175°C warmer than the air if the voltage across it is 9 V. From figure 3.5 it can be seen that R_p is about 100°C warmer than the water if the voltage across it is 9 V. In air the chip becomes about 40% of R_p temperature and in water it becomes about 7%. So the chip is more heated up in air than in water.
Figure 3.4: Rp of the PressureWire is excited (V_p) in air at 20 °C and the chip temperature is measured with R_a. The change in R_a is the change in chip temperature. It is fitted with a second order polynomial.

Figure 3.5: Rp of the PressureWire is excited (V_p) in water at 37 °C and the chip temperature is measured with R_a. The change in R_a is the change in chip temperature. It is fitted with a second order polynomial.

3.4 Discussion
To draw a conclusion from the result about the chip temperature the change of the R_a must be representative for chip temperature. But how representative is this? Perhaps R_a is isolated from the chip by vacuum under the pressure-sensitive membrane.
For the cables inside the PressureWire a constant value for the resistance is taken. This resistance is determined at 37 °C and is the cable resistance at 37 °C. In determine the temperature coefficient of $R_p$ and $R_a$ the ambient temperature is not constant, and therefore the cable resistance will change. Also for the experiment in air at 20 °C the cable resistance at 37 °C is used. In figure 3.6 the change in cable resistance due to the change in ambient temperature is plotted.

![Figure 3.6: Cable resistance versus the ambient temperature.](image)

The difference between the cable resistance at 20 °C and the cable resistance at 37 °C is about 2 Ω. So the error in the calculated temperature coefficients and the calculated temperatures of $R_a$ and $R_p$ are small.

### 3.5 Conclusion

From figure 3.5 it can be seen that the main part of the heat of $R_p$ goes to the water and not to the chip. In Air almost the same part goes to the chip as to the air. In water it is possible to use the PressureWire as a HWA application, because the most heat of the PressureWire goes to the fluid by convection. The chip temperature in water is slightly warmer than the water. Blood will not coagulate up until an excitation of 7 V of $R_p$, if the chip temperatures in water are comparable with chip temperatures in blood.
Chapter 4

Method 3: PressureWire in a CTA application

4.1 Introduction

From chapter 2 and 3 it can be seen that it is possible to use the PressureWire as a hot-wire. In this chapter a CTA circuit is designed in which the PressureWire is incorporated. With this CTA circuit an experimental set-up is designed to investigate the heat transfer from the sensor to the fluid at varying flow rate. So the constants A, B and n in equation 1.6, \( V_p^2 = A + BU^n \), can be found.

4.2 The CTA circuit and experimental set-up

A plastic tube with an inner diameter of 4 mm (approximately that of a coronary artery) is placed in a water bath (Grant) at 37.0 °C. The water bath is filled with approximately 35 liters of water. The temperature is kept constant with a thermo regulator (Techne TU 20D). This thermo regulator also creates some flow circulation in the water bath to maintain a homogenous temperature. The tube is connected to a pump to create a steady, fully developed Poiseuille flow. The flow can be change by changing the power to the pump. An ultrasonic flow meter (T110, Transonic Systems) is used for reference flow measurement.

The main part of the PressureWire (PressureWire4, Radi Medical Systems AB) is immersed in the water bath and introduced in the tube, with the sensor situated at sufficient distance from the entrance to ensure fully developed Poiseuille flow at the measurement site. The wire is aligned with the flow, in the direction corresponding with the introduction in catheterization, from the aorta into the coronary tree. By using a connector the sensor (R_p) is incorporated in the Wheatstone bridge of the CTA circuit. The output of the CTA circuit is transferred with a DAQcard-700 (National Instruments) to the measurement computer. Labview 6 controls the DAQcard-700. Also the flow meter is connected to the DAQcard-700 (figure 4.1).

Figure 4.1: Schematic representation of experimental setup
The CTA circuit
As described in chapter 1 a CTA circuit is basically a Wheatstone bridge with a feedback operational amplifier. \( R_p \) is incorporated in a Wheatstone bridge as can be seen in figure 4.2 (enclosed by the red dashed line (1)). In this circuit \( R_p \) represents the cable resistance of the cables inside the PressureWire. \( R_1, R_2, \) and \( R_4 \) are resistors with a fixed resistance and temperature independent. Capacitors are placed in the Wheatstone bridge to slow down the feedback of the amplifier (OP413 FP) to get the bridge more stable. The gain \( (G) \) of the amplifier is set by the ratio between \( R_1 \) and \( R_2 \):

\[
G = 1 + \frac{R_1}{R_2}
\]  

(4.1)

Maybe the gain is not linear in the whole range, so the gain is given a constant value by use the fixed resistance \( R_1 \) and \( R_2 \). In this circuit the gain is 2, because \( R_1 \) and \( R_2 \) have the same resistance (see appendix A for the resistance values for the resistors in figure 4.2). \( R_3 \) is used to adjust the operating temperature of \( R_p \).

Figure 4.2: CTA circuit: (1) \( R_p \) is incorporated in a Wheatstone bridge, (2) create the reference voltage \( V_{\text{ref}} \) and (3) first order filter.
Rs and the capacitor (in series with Rs) are used to insure the amplifier’s output voltage (Vex) goes positive on turn on (the amplifier is dual supplied −5 V and 25 V). In this way a pulse is created on turn on, which created a small offset current for the amplifier. This current does not influence the dc level of Vex, because the capacitor is open if the frequency is zero (ω = 0).

\[ R_{\text{total}} = R_s + \frac{1}{j\omega C} = \infty \quad \text{if} \quad \omega = 0 \tag{4.2} \]

Also the ac level of Vex is not influenced if the impedance of Rs is much higher than R1.

It is difficult to measure the Vex directly with the DAQcard-700, because its maximal range (Vrange) is ±10V. It is also better to use the card in minimal range (±2.5V) to have maximal resolution (Vresolution).

\[ V_{\text{resolution}} = \frac{V_{\text{range}}}{2^n} = \frac{5}{2^{12}} = 1.22 \text{mV} \tag{4.3} \]

n = Number of bits of the DAQcard-700

To make it possible to use the DAQcard-700 in its minimal range we measure in a differential mode and increase the ground with a reference voltage (Vref), so that Vex - Vref ≈ 1V. The circuit enclosed by the green dashed line in figure 4.2 (2) enables this reference voltage. The output of Reff 02 (MAXIM, MAX6250, BCPA0317) gives a stable voltage of 5.000V. This voltage can be adjusted with the potential meter R7, so that the range of the reference voltage is 0V to 20V. The stability of the reference voltage is ±0.001V. This is stable enough, because the resolution of the DAQcard-700 in its minimal range is 1.22mV.

Before connecting Vex and Vref to the DAQcard-700 a first order filter, enclosed by the blue dashed line in figure 4.2 (3), is used to reduce the noise. The plus input of the DAQcard-700 I/O connector is connected to the output of the first order filter (ΔV) and the minus input is connected to the ground of the system. Vex is:

\[ V_{\text{ex}} = V_{\text{ref}} + \Delta V \tag{4.4} \]

The resistors (R) in the filter have the same value to set the gain of the amplifier to 1, and therefore no amplification of the signal. The cut-off frequency of the filter is 70 Hz (\( f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi 22.10^{-6} \cdot 0.110^{-6}} \approx 70\text{Hz} \))

### 4.3 Method

Using the set-up described in the previous section a number of experiments are carried out to examine the relation between flow rate and Vex, the constants in King’s law. Instationary flow is applied to demonstrate the anemometer application of the PressureWire. In the experiment to determine the parameters in King’s law 8 different flows are used. The flow is changed by adjusting the power to the pump, approximately from 30 to 300 ml/min with steps of approximately 40 ml/min. It is difficult to adjust the flow with the pump. Only increasing protocol is used. At each
flow step \( V_{ex} \) and the flow are measured 30 seconds at a sample rate of 5 Hz. After increase of flow a few seconds are taken before the measurement to ensure a stationary situation. Measurements are started at a high overheat ratio (\( T_w/T_a \) or \( R_w/R_{ambient} \)) and the ratio is decreased until the resolution becomes too poor to discriminate between the different flow rates applied. The overheat ratio is not measured, in other words the temperature of \( R_p \) (\( T_w \)) is not measured or the resistance of \( R_p \) (\( R_{w} \)) is not monitored. If the \( R_3 \) is measured \( R_p \) at \( T_w \) can be calculated with equation (4.5). And if the resistance of \( R_p \) at \( T_a \) (\( R_{ambient} \)) is known (different for each PressureWire) the overheat ratio can be calculated, \( R_p(T_w)/R_p(T_a) \).

\[
\frac{R_1}{R_2} = \frac{(R_3 + R_4)}{(2R_e + R_p)} \Rightarrow R_p = \frac{R_2(R_3 + R_4)}{R_1} - 2R_e \quad \text{at} \quad T_w
\] (4.5)

For the highest overheat ratio \( R_3 \) is tuned at 30 ml/min, causing \( V_{ex} \) to be near 18 V. The overheat ratio is decrease by decreasing \( V_{ex} \) with steps of 2V (at 30 ml/min). This experiment is done with different sensors. The experiment is carried out twice for each sensor.

Also an experiment with a stepwise increasing and decreasing flow rate protocol is carried out to investigate possible time-dependent effects.

All the experiments are performed in water at 37.0°C.

### 4.4 Results

To illustrate the principle of the anemometer application of the PressureWire the results of an instationary flow experiment are shown in figure 4.3.

![Figure 4.3](image_url)

**Figure 4.3**: Top: applied flow. Bottom: Measured signal \( V_{ex} \), the mean of the measured \( V_{ex} \) is taken as baseline. \( R_3 \) is tuned at 30 ml/min, causing \( V_{ex} \) near 18 V.
The flow fluctuation is about 1 Hz. This fluctuation is created manually, by increase and decrease the power to the pump. In the upper graph the applied flow is shown, the resulting change in measured $V_{ex}$ is depicted in the lower graph. The measured $V_{ex}$ follows the flow very well and the shape of the measured $V_{ex}$ curve resembles that of the flow curve.

In the experiment to determine the parameters in the King’s law, 2 sensors are used. For each sensor the experiment is done twice. In figure 4.4 the result is shown for one of the sensor with $R_3$ tunes at 30 ml/min, causing $V_{ex}$ near 12 V. In the upper graph the applied flow steps are shown, the resulting change in measured $V_{ex}$ for each flow step is depicted in the lower graph. See appendix B1 for the other results.

![Graph](image1)

**Figure 4.4:** Top: applied flow steps. Bottom: Measured signal $V_{ex}$, the mean of the measured $V_{ex}$ is taken as baseline. $R_3$ is tuned at 30 ml/min, causing $V_{ex}$ near 12 V.

For each flow step the mean flow and the mean excitation voltage $V_{ex}$ are calculated. In figure 4.5 the mean squared $V_{ex}$ versus the mean flow are plotted to find the relation between the flow rate ($Q$) and $V_{ex}$:

$$V_{ex}^2 = A + BQ^n$$

with $A$, $B$ and $n$ the parameters of the King’s law. To find these parameters a least squares curve-fitting method, based on the sum of errors squared ($\varepsilon_{ss}$) is applied to the voltage difference $V_{cal}^2 - V_{ex, mean}^2$; that is [3],

$$\varepsilon_{ss} = \sum_{i=1}^{N} (V_{cal}^2 - V_{ex, mean}^2)^2$$  \hspace{1cm} (4.7)
$V_{\text{cal}}$ is the voltage calculated with the relationship 4.6, using the measured calibration flow, $Q_r$:

$$V_{\text{cal}}^2 = A + BQ_r^n \quad \text{or} \quad V_{\text{cal}}^2 = F(Q_r) \quad (4.8)$$

To minimize the $\varepsilon_{\text{ss}}$, the Nelder-Mead Simplex based algorithm is used as implemented in the Matlab’s function, `fminsearch.m`.

Figure 4.5: The mean excitation voltage $V_{\text{ex}}$ at each flow step with their standard deviation (vertical error bar). Also the standard deviation in each flow step is plotted (horizontal error bar). The data is fitted with relationship 4.6 (red line).

The parameters of King’s law (A, B and n) for the two sensors are given in table 4.1.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Overheat Ratio [V]</th>
<th>A</th>
<th>B</th>
<th>n</th>
<th>Normalized A</th>
<th>Normalized B</th>
<th>$\varepsilon$</th>
</tr>
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<td>0.0029</td>
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<td>0.330</td>
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Table 4.1: A, B and n of relationship 4.8 obtained with fminsearch.m.

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<td>-1250.7</td>
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<td>0.018</td>
<td>0.599</td>
<td>0.3776</td>
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</table>

To compare between the different overheat ratios A and B are normalized by the squared Vex at 30 ml/min. The squared Vex at 30 ml/min is obtained by relationship 4.8 using the found A, B and n.

To describe the goodness of fit the related normalized standard deviation is used, $\epsilon$:

$$
\epsilon = \left( \frac{1}{N} \sum_{i=1}^{N} \left( 1 - \frac{Q_r}{Q_{cal}} \right)^2 \right)^{1/2}
$$

(4.9)

where $Q_{cal}$ can be obtained by inverting equation 4.8 using the now-know parameters.

$$
Q_{cal} = F^{-1}(V_{ex}^2)
$$

(4.10)

From table 4.1 it can be seen that the parameters of King’s law for the two sensors differ from each other and also deviate between the two measurement series. From the normalized A and B can be seen that there is a difference between the different overheat ratios. The goodness of fit is better for sensor 1, than for sensor 2 (lower $\epsilon$). The resolution becomes too poor at an overheat ratio lower than 8 V. Only for the first measurement series of sensor 1 it was possible to measure at a 6 V overheat ratio.

In figure 4.6 the squared mean Vex at each flow step for all measurement series are plotted. All signals are set zero at 30 ml/min and normalized by the squared Vex at 30 ml/min to plot the different overheat ratios in one graph. The lines represent the curve fits. From this figure it can be seen that the difference between the sensors and between the different overheat ratios is not as large you would expect from the calculated parameters. From the plots in Appendix B1 it follows that the difference between the two measurement series at each overheat ratio are small and also the difference between the two sensors. To find out how stable the parameters of King’s law are all flow steps are omitted sequentially, after which the parameters are calculated. The results of this experiment are given in figure 4.7 and 4.8.
Figure 4.6: The squared mean $V_{ex}$ versus applied flow rate, $V_{ex}^2$ at $Q = 30$ ml/min taken as baseline and normalized by this voltage. $V_{ex}^2$ at $Q = 30$ ml/min is obtained by relationship 4.8 using the found A, B and n. Above are the results from sensor 1 and below are the results from sensor 2.

Figure 4.7: Variations in parameters of King’s law as a consequence of omit a flow step: (A) constant A, (B) constant B and (C) constant n.
Figure 4.8: The squared voltage versus the flow. The lines are obtained by relationship 4.8 and the parameters of figure 4.7.

From figure 4.7 it can be seen that the parameters B and n of King’s law are not very stable after omitting a flow step. Especially by leaving out the first and last flow step it deviates significant from the others. In spite of the difference between the parameters the curve fits are almost the same in the range of interest (0 to 300 ml/min) (only the curve fit without flow at 30 ml/min deviates from the others). So it is difficult to find one unique set of parameters.

To find a more unique set of parameters we set some restrictions for the parameters A and n. The parameter A may not become negative and n must be in the range 0.2-0.5. In figure 4.7c n is for the most cases above 0.2 and in literature 0.5 is used for conventional hot wires. Also the Matlab routine *fminsearch.m* is replaced by the routine *lsqnonlin.m*. This routine allows the above restrictions for parameter A and n. It uses a large-scale algorithm. This algorithm is a subspace trust region method and is based on the interior-reflective Newton method [4], [5].

Also the last flow step by the first series of sensor 1 and the last two flow steps by both series of sensor 2 are skipped, because the noise level was high in $V_{ex}$ (see appendix B2).

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Overheat Ratio [V]</th>
<th>A</th>
<th>B</th>
<th>n</th>
<th>Normalized A</th>
<th>Normalized B</th>
<th>$\varepsilon$</th>
</tr>
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<tbody>
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<td></td>
<td></td>
<td>0.033</td>
</tr>
</tbody>
</table>
Table 4.2: A, B and n of relationship 4.8 obtained with lsqnonlin.m.

The parameters of King’s law determined with the restrictions are given in table 4.2. The parameters deviates less between the two measurements series and between the different overheat ratios. In figure 4.9 the curve fits are plot.

In figure 4.10 are the result of the stability experiment. It can be seen that the parameter B and n are slightly more than with restriction.

Figure 4.9: The squared mean $V_{ex}$ vs applied flow rate, $V_{ex}^2$ at $Q = 30$ ml/min taken as baseline and normalized by this voltage. $V_{ex}^2$ at $Q = 30$ ml/min is obtained by relationship 4.8 using the found A, B and n. Above are the results from sensor 1 and below are the results from sensor 2.
Figure 4.10: Variations in parameters of the King’s law as a consequence of omit a flow step: (A) constant A, (B) constant B and (C) constant n. To determine the parameters restrictions for A and n are used now

The result of the experiment with a stepwise increasing and decreasing flow rate protocol is shown in figure 4.11

Figure 4.11: Left: Stepwise increasing and decreasing flow (top) and measured $V_{ex}$, the mean of the measured $V_{ex}$ is taken as baseline (bottom). Right: Mean data per flow level, increasing o, decreasing *.

The flow steps for increasing and decreasing are not the same, and therefore it is difficult to compare the resulting measured $V_{ex}$ with each other. From the right plot of figure 4.11 it can be seen that the measured $V_{ex}$ is a little bit higher for the low flow steps.

4.5 Discussion

A pump adjusts the flow. This makes it difficult to get the same flow steps in the experiment. Also it is not possible to get a stable flow (standard deviation of 5
ml/min) with the pump. This will cause fluctuation in the measured $V_{ex}$, especially at the low flow where it is more sensible for flow.

By the second measurement series of sensor 1 the tube is renewed and the temperature of the water is better regulated. So the circumstance between the two measurement series of sensor 1 are not the same regarding chip position in the tube. Between the two measurement series of sensor 2 the sensor is not taken out the tube. This can be the reason that the difference between the two measurement series of sensor 1 is bigger, than between the two measurement series of sensor 2. In the next chapter the influence of the chip position in the tube is investigated.

4.6 Conclusion

From the results of the experiments in this chapter it can be concluded, that there is clear relation between the measured voltage and flow rate. This relation can be described with the relationship 4.6. But it is difficult to find a unique set of parameters for this relationship.
Chapter 5

Method 4: Chip position and ambient temperature

5.1 Introduction

The parameters of King’s law were found in chapter 4. In chapter 4 flow is fully developed at the measurement site. This means that the maximum flow velocity is in the center of the tube and the sensor experiences the largest cooling effect in the center of the tube. In this chapter the influence of the chip position in the tube on the King’s law parameters are investigated. Also in this chapter the influence of changes in ambient temperature, ambient temperature sensitivity, on the parameters of King’s law are investigated.

5.2 Method

To verify the influence of the position of the chip on the measured voltage, and therefore the parameters of King’s law, the wire is rotated in 4 steps of \( \frac{\pi}{2} \) rad from the chip positioned left to facing downwards to right to facing upwards. The same experimental set up and CTA circuit as in chapter 4 is used. But now a constant flow of 130 ml/min is used and the overheat ratio is set by tuning R3 at 130 ml/min and chip positioned left, causing V_{ex} near 16 V. By each position of the chip V_{ex} and the flow are measured 120 seconds at a sample rate of 5 Hz. This experiment is performed in water at 37.1°C.

To investigate the ambient temperature sensitivity V_{ex} is measured by 34.1°C and four different flows. The experiment is repeat by 37.1°C using the same flows and the same overheat ratio. This experiment is done by four different overheat ratios. The ambient temperature sensitivity is defined as:

\[
S_T = \frac{\Delta V_{ex}}{\Delta T}
\]  

(5.1)

The same CTA circuit as in chapter 4 is used. The sensor is now not immersed in a tube, but lie with about 80% of its length in a water bath (Grant). The temperature is kept constant with a thermo regulator (Techne TU 20D). This thermo regulator also induces some flow circulation in the water bath to get a homogenous temperature.

5.3 Results

In figure 5.1 can be seen that the measured voltage varies considerably with the position of the chip. The different between the up and down position is about 130 mV, while the change in measured voltage due to the flow change from 30 ml/min to 250 ml/min is about 150 mV (see Appendix B) at an overheat ratio of 16 V.
Figure 5.1: Measured voltage while wire was rotated in 4 steps of $\frac{1}{2}\pi$ rad. $Q = 130$ ml/min.

Figure 5.2: The ambient temperature sensitivity

The sensor becomes more ambient temperature sensitive if the overheat ratio decreases. It also become slightly more temperature sensitive at higher flow rate (figure 5.2). The measured voltage at low overheat ratios varies considerably with changes in the ambient temperature. The ambient temperature sensitivity at an overheat ratio of 8V is about 270 mV °C⁻¹, while the change in measured voltage due to the flow change from 30 ml/min to 250 ml/min is about 80 mV (see Appendix B1).
5.4 Discussion
In the experiment with the chip position the radial position of the chip was not monitored or controlled but is assumed to be reasonably constant. In the ambient temperature experiment the flow steps are not exactly the same for the two temperatures, because it was difficult to get a constant flow with the pump.

5.5 Conclusion
As can be concluded from the results the influence of the chip and the ambient temperature on the measured voltage, and therefore the parameters of the King’s law are significant compared with the flow modulation. So the measured voltage must be corrected for changes in ambient temperature. And care should be taken in comparing measured voltages while constant wire position is not assured.
Chapter 6

Discussion

In chapter 1 we have seen how $R_p$ is heated up by itself and to what extent it can be heated by increasing the voltage across it. This model experiment shows that $R_p$ is heated up more in air than in water. From this we conclude that the conductivity in water is better than in air; more heat is directly diffused into the water than into air. During this experiment the cables inside the PressureWire are neglected, which result in a lower heat up curve of $R_p$. For the cables a constant value can be taken, because the internal heating of $R_p$ does not lead to similar increase in cable temperature because of the limited power dissipated in the cable.

In chapter 2 we assume that the change of the $R_a$ is representative of chip temperature. The chip temperature is now only measured on one place of the chip (where $R_a$ is situated), therefore it is not possible to say that the heat distribution on the chip is homogeneous. Also $R_a$ is located on a pressure-sensitive membrane and this maybe isolate $R_p$ from the chip. The get a better understanding of the heat distribution on the chip an infrared camera may be used. To do this the resolution of the infrared camera must be very high. To use the PressureWire as a flow sensor in a clinical environment it is important to have a good indication of the chip temperature. The chip may not become to warm, otherwise blood start to coagulate.

The heat transfer coefficient is a function of flow velocity ($U$) according to King’s law. But in the stationary measurements to determine the parameters $A$, $B$ and $n$ flow rate ($Q$) is used instead of flow velocity. But in fully developed tube flow the flow velocity is linearly related to the flow rate. Also the amplifier’s output voltage ($V_{ex}$) was measured and not the voltage across $R_p$ ($V_p$). The relation between $V_{ex}$ and $V_p$ is

$$V_p = V_{ex} \frac{R_p}{R_3 + R_4 + 2R_c + R_p} \quad (6.1)$$

were $R_3$, $R_4$ and $R_c$ (cable resistance) are resistances defined in figure 4.2. Equation 1.6 has to be rewritten to use the found parameters;

$$\frac{V_p^2}{R_p} (R_3 + R_4 + 2R_c + R_p)^2 = A + BQ^n \quad (6.2)$$

Instationary effects such as heating of the chip and other conduction effects are not taken into account in the stationary measurements. Therefore the results of a protocol with increasing and decreasing flow rates are present. The measured signals are quite the same for increasing and decreasing flow rates. This suggests that there is not a heating effect in the protocol.

In the instationary flow experiment the measured signal follows the flow, with a fluctuation of 1 Hz, very well. But this experiment needs more investigation regarding different flow fluctuation.
Chapter 7

Conclusion

During the training the feasibility of the use of the PressureWire as a hot-wire anemometer is investigated. If this application can be used simultaneously with the current pressure measurement in a clinical situation the Coronary Flow Reserve (CFR) and Fractional Flow Reserve (FFR), based on flow rate and pressure measurements, respectively, can be determined [1]. The contribution of an epicardial stenosis and microvascular dysfunction to the extent of inducible ischemia can be diagnosed using one single probe [1].

There are different types of hot-wire anemometer. In this report the PressureWire is used in constant temperature (CTA) mode. In steady state a relation between the excitation voltage \( V_p \) and the flow velocity can be found, by using the King’s law.

\[
V_p^2 = A + BU^n
\]  

(7.1)

In equation 7.1 A and B are velocity-independent constants. The exponent n depends on the geometry of the PressureWire sensor.

In this report the passive resistance of the PressureWire \( R_p \) is incorporated in a CTA application. From chapter 2 and 3 it can be seen that it is possible to use \( R_p \) as a hot-wire, because it is heated up when it is excited and the most heat goes to the fluid instead of to the chip. The parameter A, B and n are examined at varying flow rate in a tube with a diameter resembling that of a coronary artery. The results of this experiment model show a clear relation between measured voltage and flow rate. But it is difficult to find a unique set of parameters for this relationship. Also the influence of the chip and the ambient temperature on the measured voltage, and therefore the parameters of the King’s law are significant compare with the flow modulation. So the measured voltage must be corrected for changes in ambient temperature. And care should be taken in comparing measured voltages while constant wire position is not assured. It can be concluded that flow-rate measurement with the PressureWire is feasible. But to use the PressureWire in a clinical environment further research is needed in instationary flow measurement and use blood instead of water.
References


The resistance values in figure A.1 are:

\[
\begin{align*}
R_1 & = 2.694 \text{ kΩ} \\
R_2 & = 2.692 \text{ kΩ} \\
R_3 & = \text{potentiometer (0-500 Ω)} \\
R_4 & = 2.400 \text{ kΩ} \\
R_5 & = 21.987 \text{ kΩ} \\
R_6 & = 6.842 \text{ kΩ} \\
R_7 & = \text{potentiometer (0-10 kΩ)} \\
R_8 & = 330 \text{ kΩ} \\
R & = 22 \text{ kΩ} \\
R_c & = \text{cable resistance of the PressureWire, 45.16 Ω}
\end{align*}
\]
Appendix B1

Sensor 1
The results of the 2 measurement of sensor 1 (red first measurement, black second measurement) are plotted in figure B1.1 to B1.14. The data is fitted by using the Matlab routine \textit{fminsearch.m}

Figure B1.1: Top: applied flow steps. Bottom: Measured signal $V_{ex}$, the mean of the measured $V_{ex}$ is taken as baseline. $R_3$ is tuned at 30 ml/min, causing $V_{ex}$ near 18 V.

Figure B1.2: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 18 V.
Figure B1.3: Top: applied flow steps. Bottom: Measured signal $V_{\text{ex}}$, the mean of the measured $V_{\text{ex}}$ is taken as baseline. $R_3$ is tuned at 30 ml/min, causing $V_{\text{ex}}$ near 16 V

Figure B1.4: The mean squared $V_{\text{ex}}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 16 V
Figure B1.5: Top: applied flow steps. Bottom: Measured signal $V_{ex}$, the mean of the measured $V_{ex}$ is taken as baseline. $R_3$ is tuned at 30 ml/min, causing $V_{ex}$ near 14 V

Figure B1.6: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 14 V
Figure B1.7: Top: applied flow steps. Bottom: Measured signal $V_{ex}$, the mean of the measured $V_{ex}$ is taken as baseline. $R_3$ is tuned at 30 ml/min, causing $V_{ex}$ near 12 V

Figure B1.8: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 12 V
Figure B1.9: Top: applied flow steps. Bottom: Measured signal $V_{ex}$, the mean of the measured $V_{ex}$ is taken as baseline. $R_3$ is tuned at 30 ml/min, causing $V_{ex}$ near 10 V

Figure B1.10: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 10 V
Figure B1.11: Top: applied flow steps. Bottom: Measured signal $V_{ex}$, the mean of the measured $V_{ex}$ is taken as baseline. $R_3$ is tuned at 30 ml/min, causing $V_{ex}$ near 8 V.

Figure B1.12: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 8 V.
Figure B1.13: Top: applied flow steps. Bottom: Measured signal $V_{ex}$, the mean of the measured $V_{ex}$ is taken as baseline. $R_3$ is tuned at 30 ml/min, causing $V_{ex}$ near 6 V

Figure B1.14: The mean squared $V_{ex}$ versus the mean flow with error bars. The line represent the fit at an overheat ratio of 6 V
Sensor 2
The results of the 2 measurement of sensor 2 (red first measurement, black second measurement) are plotted in figure B1.15 to B1.26. The data is fitted by using the Matlab routine fminsearch.m.

Figure B1.15: Top: applied flow steps. Bottom: Measured signal $V_{ex}$, the mean of the measured $V_{ex}$ is taken as baseline. $R_3$ is tuned at 30 ml/min, causing $V_{ex}$ near 18 V.

Figure B1.16: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 18 V.
Figure B1.17: Top: applied flow steps. Bottom: Measured signal $V_{ex}$, the mean of the measured $V_{ex}$ is taken as baseline. $R_3$ is tuned at 30 ml/min, causing $V_{ex}$ near 16 V

Figure B1.18: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 16 V
Figure B1.19: Top: applied flow steps. Bottom: Measured signal $V_{ex}$, the mean of the measured $V_{ex}$ is taken as baseline. $R_3$ is tuned at 30 ml/min, causing $V_{ex}$ near 14 V

Figure B1.20: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 14 V
Figure B1.21: Top: applied flow steps. Bottom: Measured signal $V_{ex}$, the mean of the measured $V_{ex}$ is taken as baseline. $R_3$ is tuned at 30 ml/min, causing $V_{ex}$ near 12 V.

Figure B1.22: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 12 V.
Figure B1.23: Top: applied flow steps. Bottom: Measured signal $V_{ex}$, the mean of the measured $V_{ex}$ is taken as baseline. $R_3$ is tuned at 30 ml/min, causing $V_{ex}$ near 10 V

Figure B1.24: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 10 V
Figure B1.25: Top: applied flow steps. Bottom: Measured signal $V_{ex}$, the mean of the measured $V_{ex}$ is taken as baseline. $R_3$ is tuned at 30 ml/min, causing $V_{ex}$ near 8 V.

Figure B1.26: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 8 V.
Appendix B2

The data is now fitted with the Matlab routine *lsqnonlin.m* and the restrictions for parameter A and n are used. Red is the first measurement serie and black is the second measurement serie.

**Sensor 1**

![Graph](image)

Figure B2.1: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 18 $V$. 
Figure B2.2: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 16 V.

Figure B2.3: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 14 V.
Figure B2.4: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 12 V

Figure B2.5: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 10 V
Figure B2.6: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 8 V

Figure B2.7: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 6 V

Sensor 2
Figure B2.8: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 18 V.

Figure B2.9: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 16 V.
Figure B2.10: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 14 V.

Figure B2.11: The mean squared $V_{ex}$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 12 V.
Figure B2.12: The mean squared $V_e$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 10 V.

Figure B2.13: The mean squared $V_e$ versus the mean flow with error bars. The lines represent the fits at an overheat ratio of 8 V.