Determination of the Constituents in a Gas Mixture with a Novel GasAnalyzer

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Abstract

The thesis evaluates the GAP, Gas Analyze Prototype, which uses MEMS (Micro-electro-mechanical-system) technology to quantify up to four different concentrations in an unknown gas mixture. The GAP is based on independent bulk equations and uses density, viscosity and specific heat constants together with measurements extracted from transducers to determine the concentrations of gas elements in a gas mixture. Experiments were made where humidity, temperature, pressure and different concentrations compositions of air where tested in order to extract data for further evaluation and understanding of the limitations of the GAP. The conclusion drawn from the experiments is that it is possible to determine the concentrations of the constituents of air with the GAP. It was also found that the basic equations tend to result in unrealistic concentration values. Therefore, to get correct concentration values more complex equations should be used. Due to inadequate software, the full capacity of the prototype was not tested, i.e. only the gas-mixture of air could be tested. Further work is needed to grasp the full capacity of the GAP.
Foreword

I would like to start thanking my supervisor Mats Cardell for giving me the opportunity to work with new and interesting technology at Artema Medical AB.

I would also like to thank my supervisor, Hans Sohlström from the Microsystem Technology laboratory, patiently waiting for the material and providing relevant and inspiring guidance.

Foremost I would like to thank the employees of Artema. They made me feel welcome and a member of their team from day one. The opportunity to bounce ideas, support, motivation and fun was never far away and provided a splendid working and learning environment. I hope that there are more cooking experiences planned for us in the future.

I would also like to take this opportunity to thank my family for their love and support.
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Chapter 1 Introduction

Monitoring of gas mixtures is important in many applications, not least for human safety and the safety of the environment. Imagine a situation where a transparent toxic gas leaks out from an industrial area, and what consequences it could have if not discovered quickly. Or imagine a patient that is given anaesthetics during surgery where the balance between respiratory and anaesthetic-gases is essential for the patient's metabolic condition. These are situations where multi-gas monitors are used. Some of the gas-monitors used today are based on Mass Spectroscopy and Raman Spectroscopy. These techniques allow a wide range of analysis but are expensive both to manufacture and to maintain [1]. Other options for gas monitoring are IR light Spectroscopy and IR Photo-acoustics. There are options which are less expensive but have narrower analysis range [2]. The existing technologies are inadequate, so new solutions for obtaining the concentration values in a gas mixture are of interest.

A new multi-gas monitor principle thus provides an enhancement to the present technology. The new principle is realized in an apparatus called the GAP, Gas Analyze Prototype; it is based on micro-fluidic and micro-electro-mechanical system, MEMS, technology. With this apparatus the concentrations of four constituents in a gas mixture can be determined by using the measurements from MEMS-transducers in the GAP. With the GAP in principle any gas mixture can be determined in real time in a cost efficient manner and without need for an external operator for the calibration.

The objectives of this thesis are to answer two questions:

- Does the GAP work in reality?
- How viable is the idea behind the GAP?

To address the two questions above, experiments are made and real-time measurements are extracted from the GAP for comparison to the accuracy and capacity promised in the report [3] written by Professor Tadeusz M. Drzewiecki.

The software, “DRT GasAnalyzer” which is used to control and communicate with the GAP, is written by an engineer called Chris Brown hired by Tadeusz M. Drzewiecki. The software is written to allow measurements on air and the different
normal constituents of air. Modifications to the software were needed to be able to complete the experimental part of the work and therefore, several versions of the software were delivered from Chris during the work with this thesis.

The experimental part of the thesis was made in the labs of Artema AB, Packfors and Karolinska Institutet.

Outline

Chapter 1 introduces the reader to the objectives and contents of the thesis.

Chapter 2 reviews the equations that the GAP is based on. The dimensionless numbers, Knudsen number, Reynolds number and Mach number are introduced.

Chapter 3 deals with the different elements of the GAP and explains how the flow, pressure differences, viscosity and density are extracted. All of these are needed for the determination of the concentration of the gas-mixture. The equations for determining the concentration are called the independent bulk equations.

Chapter 4 discusses the independent bulk equations that are explained in chapter 2 and the problems encountered. For example, the discussion deals with the character of the flow and the possibility to remove the turbulent or laminar part from the equations so that they can be considered independent.

Chapter 5 explains the software that is used in the experimental part of the work and for extractions of the streamed raw data from the GAP. Also this chapter deals with the “new” updates of the software used for communication between the GAP and the computer.

Chapter 6 deals with the experimental part of the work, which includes climate test made in a climate room at Packfors and Pressure test made in a pressure-cabin at Karolinska Institutet. As the software was restricted to “air” no anaesthetic gases or alcohol where tested.
Chapter 7 discusses the result gained from the experiments. The discussion evolves also around error sources and how good the performance of the GAP is.

In chapter 8 the conclusion drawn from the experiments is that it is possible to determine the concentrations of the constituents of air with the GAP. To determine the accuracy further work is necessary.

In chapter 9 suggestions for further work are given. It is essential to gain more understanding of the software to be able to extract useful data.
Chapter 2 Basic Theory of Micro-Fluidics

2.1 Overview
Before testing the usefulness of the Gas Analyze Prototype (GAP) by experiments, a study of the equations used in the following is needed. This enables a better understanding of the restrictions for the GAP. The first chapter deals with the basic theoretical knowledge needed to model a fluid in a system of micro- or nano-scale. A short introduction of the dimensionless numbers is also given in this chapter. The discussions in following chapters are all restricted to the specific case of fluids in micro-sized systems, micro-fluidics.

2.2 A continuum modeled fluid
There are two common ways to model a micro-flow; either the flow is considered a collection of molecules and determined with the aid of approximations and numerical methods called “Computational fluid dynamics (CFD)”, or the flow can be considered a continuum as in our case. The fluid is then modeled in terms of density, velocity, pressure, temperature and other macroscopic flow quantities which are defined at every point in space and time [4]. The continuum model is “easier” to handle mathematically, due to the simplification given by the Navier-stokes, Euler and Bernoulli equations. There are only a handful of exact solutions for the Navier-stokes equation and for the Bernoulli three states must be satisfied.

2.3 Navier-Stokes equation
As we will see in the next chapter the Navier-Stokes equation is used to determine the viscosity of the gas mixture. The definition of a Newtonian fluid [5] is “a fluid for which the shear stresses is linearly related to the rate of shearing strain” and where the velocity field can be described in the Navier-Stokes equation. The Navier-Stokes equation describes motion in three dimensions combined with the conservation of mass. It describes the flow of an incompressible Newtonian fluid by a basic differential equation with the acceleration terms on the left side and the force terms on the right side, see equation 2.1, 2.2 and 2.3.
The basis for the first independent bulk equation is now visible and in order to determine the density in the next chapter a closer look at the Bernoulli’s equation is needed.

### 2.4 Bernoulli’s equation

The equation of Bernoulli requires [6] that 1) viscous effects are assumed negligible; 2) the flow is assumed to be steady; 3) the flow is assumed to be incompressible. Bernoulli’s equation origins from Euler’s equation for friction free flow which is modified from

$$\frac{\nu^2}{2} + P - U = \text{const} \quad \text{to} \quad P = \int \frac{dp}{\rho} \quad \text{and} \quad U = \text{energy}$$

and can therefore be expressed in the following way:

$$P_1 + \frac{1}{2} \rho_1 \cdot V_1^2 = P_2 + \frac{1}{2} \rho_2 \cdot V_2^2$$

The basic structure for the second bulk equation is now visible but in order to know the validity of the above equation, two dimensionless numbers are of help. Firstly the Knudsen number which determines the validity of the continuum model and secondly the Mach’s number which determines one of the statements for Bernoulli’s equation.

### 2.5 Knudsen number

The dimensionless Knudsen number $Kn$, which is defined as the ratio between the free mean path $\ell$ and the characteristic length $L$, shows whether the continuum model is
valid or not. If not, the use of a Molecular model instead is a requirement for reliable solutions. The Knudsen number expressed as follows [7]:

$$Kn = \frac{\ell}{L}$$  \hspace{1cm} (2.6)

$\ell$ is defined as the free mean path, ( $\ell$ is the average distance traveled by molecules between collisions in an ideal gas). The correlation between the free mean path and the pressure $p$ and the temperature $T$ is as follows [8]:

$$\ell = \frac{kT}{\sqrt{2\pi p\sigma^2}}$$  \hspace{1cm} (2.7)

Here $\sigma$ is the molecular diameter and $k$ is the Boltzmann constant.

The characteristic flow dimension $L$ is defined as:

$$L = \frac{\rho}{\frac{\partial \rho}{\partial y}}$$  \hspace{1cm} (2.8)

“The Knudsen number regimes” [9].

$Kn < 0.01$ \hspace{1cm} Navier-Stokes equations is valid.

$0.01 \leq Kn \leq 0.3$ \hspace{1cm} In the “Slip regime”, the Navier-Stokes equation is useful, but the boundary conditions must be modified due to the fact that at the surface the gas ‘slips’.

$0.3 \leq Kn \leq 10$ \hspace{1cm} In the “Intermediate regime” the Navier-Stokes equation must be changed and improved.

$Kn > 10$ \hspace{1cm} In the “Rarified gas regime” The Navier-Stokes equation is no longer valid.
2.6 Mach number

The dimensionless Mach number, which is the ratio of flow velocity $v_0$ to the speed of sound $a_0$ [10], determines whether the flow is compressible or incompressible, which is necessary for the validity of the Bernoulli’s equation 2.5

The Mach number is defined as:

$$Ma = \frac{v_0}{a_0}$$

(2.9)

The definition of incompressible flow,” a fluid which is not reduced in volume by an increase in pressure”, is:

$$Ma = \frac{v_0}{a_0} < 0.3$$

(2.10)

The validity of the continuum and Bernoulli’s equation are now described by the help of the two dimensionless numbers. We now introduce a third dimensionless number, the Reynolds number.

2.7 Reynolds number

The dimensionless Reynolds number, which is the ratio of inertial forces to viscous ones, determines whether the flow can be characterized as turbulent flow, laminar flow or both and will later in the chapter give a better understanding of how the fluid behaves in the GAP. The Reynolds number $Re$ is defined as [11]:

$$Re = \frac{\rho}{\mu} \cdot v_0 L$$

(2.11)

where $\rho$ is the density, $\mu$ is the viscosity, $v_0$ is the velocity of the gas and $L$ is the characteristic length. In macroscopic structures the transition to turbulent flow appears at Re equal to 2300. In microscopic structures on the other hand turbulence can appear at Re equal to 100 but to ensure turbulence the value of Re should be greater than 1000 [31].

$Re < 1$ The flow is of laminar character.

$1 \leq Re \geq 100$ The flow is of both laminar and turbulent character.
\(Re > 100\) The flow is of turbulent character.

### 2.8 Conclusion

We have now gained an understanding of the equation that will be used to determine the density and the viscosity of the gas mixture. Introductions to the dimensionless numbers are also given. Reynolds number is useful for characterizing different flow regimes. Knudsen number is useful for determining if the continuum equation is still valid when e.g. temperature or the gas mixture changes. The Mach number is useful for checking that the flow is incompressible so all three statements are fulfilled for Bernoulli’s equation.
Chapter 3 The Different Structures of the Gas Analyze Prototype

3.1 Overview

While the first chapter explains the use of a continuum model, the dimensionless numbers and introduces the restrictions that need to be considered to ensure validity of the equations, the second chapter explains the structure of the gas analyze prototype, GAP, and how the theory of the micro-fluidics is correlated to the different parts.

The function of the GAP is to evaluate a gas mixture with maximum four different elements [12]. The hardware of the GAP is divided into different blocks, see Figure 1: an acoustic transmission-line, a micro fluidic sensor consisting of an orifice, a micro-fluidic oscillator and capillaries, MEMS-transducers, and a pump which pumps the gas-mixture around. Measurements are extracted from the block which together with four equation yields the wanted concentration of the elements.

The word MEMS stands for Micro-electro-mechanical system. This means an integration of elements, in micro scale, such as sensors, motors and circuits of the size of microns.

![Figure 1, system overview of the GAP](image)
Furthermore this chapter introduces the four independent bulk equations, together with geometrical constants and the measurements from the transducers the concentration of the constituents of a test gas can be determined.

3.2 Acoustic transmission line

The first evaluation of the test-gas, which is pumped through the GAP, is made in the acoustic transmission line. An acoustic transmitter is placed in the beginning of the 63.5 mm long, 1.8 mm diameter drilled pipe, with a microphone in the end. The time it takes for a pulse generated from the transmitter to travel to the microphone is called the time delay $\tau_d$, $L_c$ is the distance between the transducers and is used for calculation of the acoustic propagation speed $c$, as

$$c = \frac{L_c}{\tau_d} \quad (3.1)$$

3.2.1 Independent bulk equation nr 1:

In order to determine the first independent bulk equation, the variable $c_p$, specific heat at constant pressure, is quantified by determining the sound of speed $a_{Mix}$ [13].

$$c_{Mix} = \frac{1}{T_0 \left( \frac{\rho_{Mix}}{\rho_0} - 1/a^2 \right)} \quad (3.2)$$

Where

$$a_{Mix} = \left\{ \frac{\left[ 1 - (1/b') (\mu_{Mix}/\pi \rho_{Mix} F_0)^{1/2} \right]}{2 \left[ (1.91 P/\rho_{Mix})^{1/2} (1/b') (\mu_{Mix}/\pi \rho_{Mix} F_0)^{1/2} + \tau_{delay}/L_s \right]^2} + \left[ 1 - (1/b') (\mu_{Mix}/\pi \rho_{Mix} F_0)^{1/2} \right] \right\}^{1/2}$$

$$+ \left\{ \frac{\left[ 4 \left[ (1.91 P/\rho_{Mix})^{1/2} (1/b') (\mu_{Mix}/\pi \rho_{Mix} F_0)^{1/2} + \tau_{delay}/L_s \right]^2 + (1.91 P/\rho_{Mix})^{1/2} (1/b') (\mu_{Mix}/\pi \rho_{Mix} F_0)^{1/2} \right]}{\left[ (1.91 P/\rho_{Mix})^{1/2} (1/b') (\mu_{Mix}/\pi \rho_{Mix} F_0)^{1/2} + \tau_{delay}/L_s \right]^2} \right\}^{1/2} \quad (3.3)$$

Substituting equation 3.4 and 3.3 with equation 3.2 the first independent bulk equation is gained [13]:

$$c_{Mix} = \frac{(C_1 c_p \rho_i)}{\rho_{Mix}} \quad (3.4)$$
The test gas then goes on to the micro fluidic sensor which will be explained in the chapter below.

3.3 The micro-fluidic sensor created by steel laminates

Seen from the outside it’s hard to imagine that the 25x25x50 mm³ box could be of any importance, while it in reality, it consists of a few dozen thin 0.002-0.004 mm glued laminates of stainless steel forming the micro-fluidic sensor. There are holes forming patterns on the laminates in different sizes, and when glued together they form a three-dimensional micro channel that consists of an orifice, a micro-fluidic oscillator and capillaries, see Figure 2.

![Figure 2, micro-fluidic sensor laminates](image)

3.3.1 Orifice

When the test gas reaches the micro-fluidic sensor the gas is first pumped through an orifice. The use of an orifice, see Figure 3, in this application is to exclude the laminar part of the flow to make it possible to determine the density $\rho_{\text{Mix}}$. This is done by measuring the pressure drop $\Delta P_{\text{Orifice}}$ with a differential pressure transducer and volumetric flow $Q_{\text{Mix}}$ through a micro-fluidic flow oscillator.
Substitution of Bernoulli’s equation (2.4) together with the $\rho = \text{Const}$ gives

$$Q = V_1 A_1 = V_2 A_2,$$

the density can be expressed in the following way;

$$\Delta P_{\text{Orifice}} = \frac{1}{2} \left( \frac{1}{A_2^2} - \frac{1}{A_1^2} \right) \cdot \rho_{\text{Mix}} \cdot Q_{\text{Mix}}^2$$  \hspace{1cm} (3.5)

$$\rho_{\text{Mix}} = 2 \cdot \frac{A_2^2 A_1^2}{A_1^2 - A_2^2} \cdot \Delta P_{\text{Orifice}} \cdot \frac{1}{Q_{\text{Mix}}^2}$$  \hspace{1cm} (3.6)

where the acoustic transmission line has a circular area of the $A_1 = \pi r^2 / 2$ m² with $r = 1.8 \cdot 10^{-3}$ m and the orifice has a quadratic area $A_2 = (d_{\text{ori}})^2$ m² where $d_{\text{ori}} = 2.9883 \cdot 10^{-4}$ m, see appendix A.

### 3.3.2 Independent bulk equation nr 2:

The second independent bulk equation 3.7 is obtained by inserting equation (3.6) in (3.7) [3]

$$\rho_{\text{Mix}} = \sum C_i \rho_i \quad i = 1, 2, 3, 4$$  \hspace{1cm} (3.7)

Secondly, after the orifice, the test gas is pumped through the capillaries.

#### 3.3.3 Capillary

The use of capillaries, see Figure 4, in this application is for the exclusion of the turbulent part of the flow for the ability to determine the viscosity $\mu_{\text{Mix}}$. This is done by measuring the pressure drop $\Delta P_{\text{Cap}}$ with a differential pressure transducer and volumetric flow $Q_{\text{Mix}}$ through a micro-fluidic flow-oscillator.
This is obtained through the relations between viscosity, pressure drop and volumetric flow. The flow is fixed between parallel plates and considered as steady and laminar. The velocities \(v\) and \(w\) in equation (2.1) and (2.2) are zero since the gas moves in the direction of \(x\). The flow is considered as an incompressible flow that follows \(\partial u/\partial x = 0\), and for steady flow \(\partial u/\partial t = 0\) so that \(u = u(y)\) [14]. With these conditions an exact solution can be obtained for the Navier-Stokes equation (2.1)-(2.3).

\[
0 = -\frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial y^2}\right) \tag{3.8}
\]
\[
0 = -\frac{\partial p}{\partial y} - \rho g \tag{3.9}
\]
\[
0 = -\frac{\partial p}{\partial z} \tag{3.10}
\]

Integrating equation (3.8), (3.9) and (3.10) together with the boundary conditions \(u=0\) and \(y=h\) the volume rate of flow is found from the relationship:

\[
Q = \int_{-h}^{h} u \, dy = \int_{-h}^{h} \frac{1}{2\mu} \left(\frac{\partial p}{\partial x}\right) \left(y^2 - h^2\right) dy \tag{3.11}
\]

or

\[
Q = -\frac{2h^3}{3\mu} \left(\frac{\partial p}{\partial x}\right) \tag{3.12}
\]

Here \(-\partial p/\partial x = \Delta P_{\text{Cap}}/L_{\text{Cap}}\) and therefore the equation (3.12) can be expressed as:

\[
\Delta P_{\text{Cap}} = \frac{3L_{\text{Cap}}}{2h^3N} \mu_{\text{Mix}} Q_{\text{Mix}} \tag{3.13}
\]

\[
\mu_{\text{Mix}} = \frac{2h^3N}{3L_{\text{Cap}}} \cdot \Delta P_{\text{Cap}} \cdot \frac{1}{Q_{\text{Mix}}} \tag{3.14}
\]
With the values gained from appendix A, $L_{\text{Cap}} = 0.0947 \text{ m}$, $h_{\text{Cap}} = d_{\text{Cap}}/2 \text{ m} = 5.81 \cdot 10^{-4}/2 \text{ m}$, and $N=11$.

3.3.4 Independent bulk equation nr 3:
The mixing relationship for viscosity [3] is obtained from the equation 3.15:

$$
\mu_{\text{Mix}} = \sum_i C_i \mu_i / \left[ C_i + \sum_j C_j \Phi_{ij} \right] \quad j \neq i, \quad i, j = 1, 2, 3, 4
$$

(3.15)

where the concentration of a specific is gas is $C_i$ and the viscosity of the specific gas is $\mu_i$.

$$
\Phi_{ij} = \left[ 1 + (\mu_i/\mu_j)^{1/2} (M_j/M_i)^{1/4} \right]^{2} / \left[ 2.828(1 + M_i/M_j)^{1/2} \right]
$$

(3.16)

Substitution of equation (3.14) and (3.16) with (3.15) results in the third independent bulk equation [3].

There is one more independent bulk equation to consider.

3.3.5 Independent bulk equation nr 4:
The last independent bulk equations is the summation of the concentrations i.e.

$$
C_1 + C_2 + C_3 + C_4 = 1
$$

(3.17)

3.3.6 Micro fluidic oscillator
The micro-fluidic oscillator, see Figure 5, is placed between the orifice and the capillaries in the micro-fluidic sensor. The oscillator is injected with a gas jet, through the supply port and the gas progresses in to the feedback loop with help from the Coanda effect. The Coanda effect refers to the phenomenon where a stream of air or another fluid emerged from a nozzle has the tendency to follow a nearby minor curved surface [15]. The gas flow follows the curve into a feedback loop and pushes the flow to the opposite wall repeating the procedure. This generates an oscillation which creates an audible tone with a specific frequency that a microphone captures. The frequency is directly proportional to the gas flow $Q$ and expressed in the following equation (3.18), where $\tau_t$ is the transmission time, $\tau_s$ is the switching time, $a$ and $b$ are constants and $Q$ is the volumetric flow rate.
In order to extract measured values from the micro-fluidic sensor MEMS transducers are used and explained in the next chapter.

3.4 Differential pressure transducer

3.4.1 Used with a orifice

The Differential Pressure Transducer is used for measuring the pressure difference in the orifice for a specific gas-flow [16]. The differential transducer, see Figure 6, measures the pressure difference between the sides of the orifice so that when the gas flows through the orifice, a pressure difference is obtained and a deflection occurs on the silicon membrane. The physical pressure deflection is transformed via a converter into electrical outputs, which is followed by a change in resistance in the bridge circuit. The Wheatstone bridge circuit has two legs with two serial connected resistors $R_1, R_3$ and $R_2, R_4$ where $R_1, R_3, R_2$ are known in prior up to high precision [17]. Therefore when the pressure changes and deflection occurs, the resistance in $R_i$ changes the zero balance between point $B$ and $D$, see Figure 7.

\[ f = \frac{1}{(2 \cdot (\tau_r + \tau_s))} = a + b \cdot Q \] (3.18)
3.4.2 Used with a capillary

The Differential Pressure Transducer used for determining the pressure difference in the capillaries is of the same brand as the one used for the Orifice.

The transducers used for the capillaries and orifice have a variable voltage offset and during initialization the voltage offset is measured as a part in the self-calibration process of the GAP. The correspondence of pressure in Voltage to pressure in Pascal is:
\[ \text{Pressure (Pa)} = \frac{\text{Pressure range}}{\text{Voltage Span}} \cdot (V - V_{\text{Offset}}) \]  
\[ (3.19) \]

For the differential transducers

\[ \text{Pressure (Pa)} = \frac{5 \cdot 459.089}{4} \cdot (V - V_{\text{Offset}}) \]  
\[ (3.20) \]

### 3.5 Absolute pressure transducer

The absolute pressure transducer works with the same basic principles as the differential pressure transducer, with the exception to the reference gas. Instead of having two inlets and test gas on each sides of the membrane, the absolute pressure transducer has one inlet, see Figure 8, with the test gas on one side and vacuum on the other side [16]. When the pressure changes the membrane deflects and a voltage change is detected.

![Figure 8, illustration of an Absolute Pressure Transducer [30]](image)

The conversion of voltage to pressure in Pascal for the absolute transducer is:

\[ \text{Pressure (Pa)} = \frac{15 \cdot 6894.8}{4} \cdot (V - 0.25) \]  
\[ (3.19) \]
3.6 Resistance temperature detector (RTD)

The absolute temperature $T$ is measured with the Thin-Film PT100 transducer, which is a Resistance Temperature Detector (RTD). The RTD has a thin layer of platinum on a substrate which changes with temperature [18]. The platinum element has a nominal resistance of 100 ohm at 0°C and increases linearly with absolute temperature and follows the equation:

$$
R_T = R_0 \left[ 1 + aT + bT^2 + cT^3 (T - 100) \right] 
$$

For $< 0^\circ C$, $R_T = R_0 \left[ 1 + aT + bT^2 \right]$  \hspace{1cm} (3.20)

For $> 0^\circ C$, $R_T = R_0 \left[ 1 + aT + bT^2 \right]$  \hspace{1cm} (3.21)

where $R_T$ is the resistance at temperature $T$, $R_0$ is the nominal resistance and $a$, $b$ and $c$ are constants used to scale the RTD, see Table 1.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Temperature Coefficient (a)</th>
<th>$a$</th>
<th>$b$</th>
<th>$c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Din 43760</td>
<td>0.003850</td>
<td>3.9080\cdot10^{-3}</td>
<td>-5.8019\cdot10^{-7}</td>
<td>-4.2735\cdot10^{-12}</td>
</tr>
<tr>
<td>American</td>
<td>0.003911</td>
<td>3.9692\cdot10^{-3}</td>
<td>-5.8495\cdot10^{-7}</td>
<td>-4.2325\cdot10^{-12}</td>
</tr>
<tr>
<td>ITS-90</td>
<td>0.003926</td>
<td>3.9848\cdot10^{-3}</td>
<td>-5.8700\cdot10^{-7}</td>
<td>-4.0000\cdot10^{-12}</td>
</tr>
</tbody>
</table>

Table 1. Callendar-Van Dusen Coefficients Corresponding to common platinum RTDs

3.7 Conclusions

By explaining the hardware of GAP we now know how to extract the four independent bulk equations and with that also the knowledge how to extract the four different concentrations in a gas mixture. What we are lacking at the moment are the measured values to put in the equations and therefore the next step is to collect data from experiments.
3.8 A detailed block-system overview of the GAP

Figure 9, a system overview of the GAP
Chapter 4 Critical Pitfalls

4.1 Overview

There are questions that emerge from the chapters above and need to be discussed before continuing on to the experimental part of the thesis. For example what does Reynolds number say about the character of the flow in the orifice and capillaries, can they really be considered independent from each other? If not, what effect will it have on the overall picture? Or what about the fact that while the flow is calculated from the frequency, gained from the oscillator with specific geometrics, the pressure difference is measured in the orifice/capillaries with different geometrical standards. Does it matter that the measurement of the flow is determined independently from the pressure measurement? An attempt to clarify this is therefore made in this chapter by going through the independent bulk equations and describing the two different critical pitfalls that are of interest.

4.2 Dependent vs. independent

The second independent bulk equation (3.7) states that the pressure difference $\Delta P_{\text{Orific}}$ in the orifice is only dependent on the turbulent part of the equation i.e. $k_4 \rho_{\text{Mix}} Q_{\text{Mix}}^2$.

The calculation of Reynolds number from equation (2.11) with the values $\rho_{\text{air}} = 1.205 \text{ kg/m}^3$, $\mu_{\text{air}} = 1.511 \times 10^{-5} \text{ m}^2/\text{s}$, $v_{\text{ori}} = 13.06 \text{ m/s}$, $Q_{\text{Mix}} = 1.17 \times 10^{-6} \text{ m}^3/\text{s}$ and the approximated diameter $d = 2.9883 \times 10^{-4} \text{ m}$ calculated in appendix A, gives $Re=311$, see Appendix B. This implies, see equation (2.11), that the character of the flow is turbulent but might include a laminar part as well. In order to fully ensure turbulence the value of Reynolds should be close to 1000 [31]. Since it is not obvious that the flow only consist of a turbulent part, a better way to express the pressure changes due to changes in the flow is to include the laminar part as seen in following equation:

$$\Delta P_{\text{ori}} = k_3 \mu_{\text{Mix}} Q + k_4 \rho_{\text{Mix}} Q^2$$  \hspace{1cm} (4.1)

where $k_3$ and $k_4$ are constants reflecting the geometry, see appendix A.
The third independent bulk equation (3.15) states that the pressure difference $\Delta P_{\text{cap}}$ in the capillary is only dependent on the laminar flow $Q_{\text{Mix}}$. To better understand how the flow behaves, the Reynolds number, see equation (2.11) is calculated with the values, $\rho = 1.205$ kg/m$^3$, $\mu_{\text{Mix}} = 1.511 \cdot 10^{-5}$ m$^2$/s, $v_{\text{cap}} = 3.46$ m/s, $Q_{\text{Mix}} = 1.17 \cdot 10^{-6}$ m$^3$/s and the approximated diameter $d_{\text{cap}} = 5.8060 \cdot 10^{-4}$ m calculated in appendix A. This gives $Re=160$, see appendix B, and implies that the character of the flow is also turbulent. This means that a better way to express the pressure changes due to changes in the flow is:

$$\Delta P_{\text{Cap}} = k_1 \mu_{\text{Mix}} Q + k_2 \rho_{\text{Mix}} Q^2$$  \hspace{1cm} (4.2)

where $k_1$ and $k_2$ are constants reflecting the geometry see appendix A.

Therefore when determining the values of $\mu_{\text{Mix}}$ and $\rho_{\text{Mix}}$ equation 4.1 and 4.2 are used instead of second and third independent equation 3.7 and 3.15 together with the measured values of the differential pressure and flow.

In Figure 10 the plot is an example of how the pressure difference in the capillary could change when the flow is increased or decreased. The plot shows two different pressure differences in the capillary, one calculated with the independent bulk equation 3.15 which doesn’t include a turbulent part and the second pressure difference calculated according to equation 4.2 which includes a turbulent part.

![Figure 10, how the differential pressure changes when the flow is changed in the capillaries](image-url)
Figure 11 shows an example of how the pressure difference in the orifice could change when the flow is increased or decreased. The plot shows two different pressure differences in the orifice, one calculated with the independent bulk equation 3.15 which doesn’t include a laminar part and the second pressure difference calculated according to equation 4.2 which includes a laminar part.

![Figure 11, How the pressure difference in the orifice changes when the flow is changed in the orifice.](image)

In the report from Tadeusz M. Drzewiecki [19] the author claims that the concentration of the gas mixture is determined with the independent bulk equations. But as can be seen in Figure 10 and Figure 11 there is a variation between the pressure differences and in order to determine if the turbulent/laminar part in the capillary/orifice is so small that it can be neglected, experimental results are needed in form of pressure and flow measurements.

### 4.3 What about the frequency?

One critical variable is the flow rate which originates from the frequency, as it is used in all of the independent bulk equations. The frequency is determined in the micro fluidic oscillator which lies between the orifice and the capillaries. When reflecting over the sampled frequency, questions arise like; Is the sampled frequency used in the calculation of the orifice same as in the calculation of the capillaries or is a mean value of a quantity of frequency samples used in the calculation of the orifice and the capillaries?
Also all gas-mixtures can not be determined with the linear equation (3.18) which is why equation (4.3) is used instead. There is no information to take part of which gas-mixtures can and which gas mixtures can not be determined with the linear equation.

\[ f = \frac{1}{2\left(\frac{k_5}{Q_{Mix}} + \frac{k_6}{c_{Mix}} + \tau_{\text{Delay}}\right)} \]  

where \( k_5/Q_{Mix} \) is the flow rate transit delay and \( k_6/c_{Mix} \) is the acoustic feedback delay, together with the amplifier response time constant \( \tau_d \) the frequency becomes a function of the total oscillator time.

4.3 Conclusion
It is important to review the measured frequency from the experiment to dismiss the possibility of any sensor failure and subsequently determinate the accuracy of the frequency. The micro-fluidic oscillator frequency is used for determining the volumetric flow rate \( Q_{Mix} \), see equation (3.18), and in order to minimize the error source in \( Q_{Mix} \) and consequently the accuracy of the density and viscosity the frequency needs to be verified. The importance lies in knowing what the cost in precision will be if only first order terms are used, i.e. the independent bulk equations. For this real data is needed.
Chapter 5 Software

5.1 Overview
A short overview of the software used in the experiments is necessary before continuing to the experimental part of the work. The GAP is dependent on two different software pieces for exchanging information and collecting streamed data. The DRT-GasAnalyzer is used for initialization of the GAP and plots the concentration curves in real-time. Then there is the HERCULES, which provides the ability to capture and save the stream data from the GAP. Both pieces of software are used simultaneously during all the tests.

5.2 DRT-GasAnalyzer
The software DRT-GasAnalyzer see Figure 12, is created by an engineer called Chris Brown hired by Tadeusz M. Drzewiecki, and used to set up a communication between the PC and GAP via the COM1 port. When the GAP is used for a specific gas mixture, the user can follow the different concentration plots in real time.

![Figure 12, the software GasAnalyzer](image)

Figure 12, the software GasAnalyzer
The values of the pump voltage and smoothing parameter can be chosen manually in the GasAnalyzer, see Figure 13. The standard value of the pump voltage is 6.25 V and the standard value of the smoothing parameter is 0.2.

A user introduction is given together with the DRT-GasAnalyzer files written by the external partner, see Appendix D. During the progress of the work, five different software versions were released as followed:

5.2.1 Version v01.01.411:
In the first version, the GAP can be started and curves containing the concentration plotted against time can be seen in graphs. Due to the lack of network compatibility, no numeric data can be collected. The v01.01.411 is only valid for testing air.

5.2.2 Version v01.01.433:
In the second version, network compatibility is included and raw data in the form of time and concentration for Carbon dioxide, Oxygen and Nitrogen is supposed to be transferred. Due to a missing .dll file, this version doesn’t work at all.
5.2.3 Version v01.01.444:
In the third version the missing .dll file is included, but it’s functionally is the same as in version v01.01.433.

5.2.4 Version v01.01.499:
In the fourth version the optimization algorithm was improved, but with no new functions added.

5.2.5 Version v02.01.464:
In the fifth version new functionality is gained, which enables the user to extract more real time data. This version is only valid for testing air.

5.3 Matlab
The software package MATLAB is used for the numerical calculations of the independent bulk equations [20].

5.4 User datagram protocol - UDP
User Datagram Protocol is a part of a communication protocol, called the Internet Protocol Suite, designed for the internet network. UDP uses datagrams which compared to packages are an “unreliable” way of exchanging information. The term unreliable refers to a system that does not notify the user if a delivery has failed or duplication has occurred. The advantage with an “unreliable” system is the decrease of time consumption due to avoidance of checking the package arrivals. Through the embedded UDP function in MatLab the raw data is streamed from the GAP to an m-file. [21]

To make this possible the UDP function needs to include a MatLab Executable, mex file. The mex-file uses a compiler to convert C/C++ or FORTRAN routines to m-files in MatLab and vise versa so that the user doesn’t need to rewrite the information being sent or received between the applications. [21]

The received packages where bigger than the maximum size allowed by MATLAB making it impossible to use this particular function. Therefore it is necessary to use software called Hercules that can collect raw data.
5.5 Hercules

To be able to collect and store the real time data from the GAP, a cross connected network cable is used to connect the GAP together with the Hercules [22], to the PC.

The software Hercules, created by the HW group, contains a serial port terminal (RS-485 or RS-232 terminal), and TCP/IP terminal and a UDP/IP terminal. The UDP tab in Hercules, see Figure 14, is used to save the streamed log-data from the GAP on to the computer.

![Figure 14, the software Hercules](image)

The IP address 127.0.0.1, the standard loopback network connection, the port number is 23 and the local port number is 7755, is chosen. To save the log-data, right click on the box named received data and click on the Log to file. Choose Log to file to set the directory of the saved stream-data and then click on Log Enable to start collecting data.

5.6 Breath simulator

If a person breaths into the GAP it is not possible to exhale the same amount of air consequently throughout the test at the same frequency. In order to simulate exhalation e.g. an adult exhales approximately 12 breaths per minute whereas an infant exhales almost 120 breaths per minute, the software Breath Simulation (BS), see Figure 15, is used together with the “Breath module“, see Figure 16.
The two plastic bags, see Figure 16, are filled with the chosen test gas, connected to the breath module and connected to the computer with the software *Breath Simulator-BS*. via Comport 4. The breath module, in turn, is connected from the outlet to the GAP via a plastic tube of 5 mm. In order to change the frequency of the breaths' adjustments are made in the box “breath rate” in the breath simulator. The BS has two modes, on and off. When the mode is on, test gas from the plastic bags are pumped from the breath modules outlet into the GAP for evaluation. When the mode is off the test gas from the plastic bags is not used instead the air in the room is pumped into the GAP for evaluation.

Figure 15, the software “Breath Simulator”

Figure 16, the “Breath module”
Chapter 6 The Experimental Setup

6.1 Overview
In the previous chapters we have defined some basic properties, checked the significance of the continuum model in theory and discussed the critical restrictions. While the theory has given us a good framework, this thesis focuses mainly on the actual testing of the GAP, see Figure 17. Since the GAP is only in the first stages of evaluation the interests was firstly to establish the fact that it works. If so, how accurate are the measurements and can the GAP be used in a medical application? In order to evaluate the GAP properly a variety of tests were performed to get a good overview of its abilities and drawbacks.

During the work different software version was received which added a second dimension to the testing. The drawbacks where the lack of insight in the logic behind the software and the inability to extract analog sensor data, the only raw-data extracted during the experiments was time and the concentration of oxide, nitrogen and carbon dioxide, albeit the concentrations are determined among others from a composition of pressure flow and time delay.

![Figure 17, the breath-the GAP](image)

The communication between the GAP and the computer was extracted via the COM1 port and test software written by an external partner. Throughout the thesis project new software versions were received and used for the testing.
The concentration measurements are executed in two different which are called dynamic and static testing. During static testing, either the air in the room or the gas from gas bottles with preselected gas concentrations is pumped through the GAP. During dynamic testing, a test person breathes into the GAP with the help of a mouthpiece.

The error source is bigger during dynamic testing as the “test gas”, in this case air, is first inhaled, warmed up in the lungs and then exhaled into the GAP with a higher carbon dioxide concentration.

6.2 Concentration measurements

6.2 1 Part 1, heat and humidity tested with software version 01.01.444

The heat and humidity test was performed in a climate room at STFI-Packforsk in Kista, Stockholm. Inside the climate room, a size of 3x5 m², the GAP and a laptop was placed on a table. In the room, the temperature and humidity could be regulated to different levels. This was done in order to get an understanding of the results of testing the GAP with humid air with its different thermodynamic constants.

There is a second interesting aspect, namely the Knudsen number see equation (2.6) which states that the Knudsen number is dependent on the temperature. The question arises of what happens with the validity of the continuum model with changes in temperature.

The tests were executed both statically and dynamically at temperature of 20°C with the humidity 20%RH, temperature of 20°C with the humidity 70%RH and temperature 40°C with the humidity 20%RH. No test was performed at the temperature of 37 °C and 100% RH due to risk of water condensation on the electrical circuits.

Setup

During the climate experiment the GAP see Figure 18 was placed on a table inside the climate room.
The Experiments are divided into two parts; where the first part of the experiment is to test the GAP statically see Figure 19. When the chosen temperature and humidity in the climate room is reached, the Hercules is set (see chapter 5.5) and the Gap is initialized with the version 01.01.444, see Appendix D. In the software “Gas Analyzer” the pump voltage is set on 6.25 V and the smoothing parameter on 0.2. After the initialization the “start data” button is pushed and the air in the climate room is pumped through the GAP throughout the test for three times for approximately three minutes each.

In the second part of the experiment, the GAP is tested dynamically see Figure 20. Before initialization of the GAP a mouthpiece is connected see Figure 17. The mouthpiece has the form of a small cylinder and is there to simplify the inhalation to the GAP. The software Hercules is set (see chapter 4.5), and a shorter initialization procedure of the GAP with the version 01.01.444 is completed, as the GAP already has been initialized properly once when tested statically. In the software “Gas Analyzer” the pump voltage is set on 6.25 V and the smoothing parameter on 0.2. When the “start data” button is pushed the inhaled air is pumped through the GAP throughout the test for three times for approximately one minute each.
Result

The plots below show three different experiments, namely the first experiment with a temperature of 20°C and humidity 20 %RH tested both statically and dynamically, the second experiment with a temperature of 20°C and humidity 70 %RH tested both statically and dynamically and the third experiment with the temperature of 40°C and humidity of 20% RH tested both statically and dynamically. The main reason for the experiments is to determine if the temperature and humidity will interfere with the determination of the concentrations.

Static temperature and humidity experiment

The three figures below shows the concentration of air divided into the constituents of nitrogen, oxygen and carbon dioxide plotted against real time data. The measurements where collected statically in the climate room.

The first figure, Figure 21 shows the concentration plotted against real time data with the temperature of 20°C and humidity 20 %RH.
The average concentration of nitrogen is 78.9 % with the standard deviation of 1.36, the average concentration of oxygen is 20.6 % with the standard deviation of 0.92 and the average concentration of carbon dioxide is 0.493 % with the standard deviation of 0.46.

The second figure, Figure 22 shows the concentration plotted against real time data with the temperature of 20°C and humidity 70 %RH.

The average concentration of nitrogen is 79.6 % with the standard deviation of 0.41, the average concentration of oxygen is 20.0 % with the standard deviation of 0.40 and
the average concentration of carbon dioxide is 0.316 % with the standard deviation of 0.15. In addition, see Figure 22, after 20 ms in the concentration measurements start to oscillate.

The third figure, Figure 23 shows the concentration plotted against real time data with the temperature of 40°C and humidity 20 %RH.

The average concentration of nitrogen is 81.7 % with the standard derivation of 1.84, the average concentration of oxygen is 18.6 % with the standard deviation of 1.56 and the average concentration of carbon dioxide is -0.294 % with the standard deviation of 1.33. Observe that the concentration of carbon dioxide is negative which can be considered as an incorrect concentration value.

**Dynamic temperature and humidity experiment**

The figures below shows the exhaled air plotted as the concentration of nitrogen, oxygen and carbon dioxide against streamed time data. The measurements were collected dynamically in the climate room.

The first figure, Figure 24, shows the concentration plotted against real time data with the temperature 20°C and humidity 70 %RH.
Figure 24, climate test1_4 with the Temperature=20 and Humidity=70%

The average of the top 10 concentration values of nitrogen is 79.8 %, the average of the top 10 concentration values of oxygen is 21.8 % and the top average of the 10 top concentration values of carbon dioxide is 3.06 %.

The second figure, Figure 25, shows the concentration plotted against real time data with the temperature 20°C and humidity 20 %RH.

Figure 25, climate test4_2 with the Temperature=20 and Humidity=20

The average of the top 10 concentration values of nitrogen is 80.2 %, the average of the top 10 concentration values of oxygen is 21.1 % and the top average of the 10 top concentration values of carbon dioxide is 2.24 %.
The third figure, Figure 26, shows the concentration plotted against real time data with the temperature 40°C and humidity 20 %RH.

![Graph of concentration against real time data with temperature 40°C and humidity 20% RH.](image)

**Figure 26, climate test with the temperature 40°C and Humidity 20% RH**

The average of the top 10 concentration values of nitrogen is 81.0 %, the average of the top 10 concentration values of oxygen is 21.1 % and the top average of the 10 top concentration values of carbon dioxide is 2.93 %. 

**Sources of error**

As written in the appendix D of how to initialize the GAP an important part is that the transducers are calibrated with normal temperature and dry air. This was impossible to achieve during the “Climate and Humidity test” for two reasons, firstly due to the fact that the initialization was started when the wanted test temperature and humidity was reached, and secondly because the software is only in the first stages of development and crashes regularly. Every time it crashes initialization is necessary for restart.

The second interesting part was to determine if the humidity would have any effect on the accuracy of the measurements, but due to the lack of stream data there is not enough information about the humidity, why it can only be considered as an uncertainty.
The third uncertainty is the temperature due to the lack of streamed real time temperature measurements there is nothing to compare the outside temperature with the measured one inside the GAP.

**Discussion**

The expectation was to see if the GAP could produce reasonable concentration values of air, i.e. nitrogen, oxygen and carbon dioxide during the heat and humidity test.

By comparing the first two figures in the static experiment, Figure 21 and Figure 22 where the change in humidity increases from 20 %RH to 70 %RH the difference in the concentration values are negligible even though oscillation occurs in Figure 22. Both figures show concentration values close to the correct air concentration. In Figure 23 the temperature is changed and oscillation occurs but compared to the two others static experiments the concentration of carbon dioxide is negative which shows problems with the structure as the summation of the concentration should be one.

In the dynamic experiments, Figure 24, Figure 25 and Figure 26 the concentration values of nitrogen, oxygen and carbon dioxide are close to the expected air concentration. When the humidity is low i.e. 20 %RH see Figure 25 the noise in the nitrogen increases, which also can be seen in Figure 26 where the temperature is higher.

**6.2.2 Part 2, pressure chamber, test performed with software version 01.01.444**

The second test was performed at Karolinska institutet, where a pressure chamber was used for the evaluation of the GAP’s performance in three different pressures 699, 1060 and 1200 mbar.

The experiment with the pressure 1200 mbar didn’t give any measurements due to the capacity of the sensors which don’t support the high pressure.

Chapter 3 discusses the fact that the differential pressure in the orifice is proportional to the flow and that the differential pressure in the capillaries are quadratic proportional to the flow. It is of interest to see if this is true even when the pressure is not atmospheric.
Setup
The GAP was placed on a table inside a pressure cabin and the door to the cabin was bolted closed see Figure 27. From the outside an operator adjusted the wanted pressure for the experiment. There are two parts in this test as well, namely the experiments were executed statically, see Figure 19, and dynamically, see Figure 20.

The first part of the testing is the static test which starts when the wanted pressure is reached. The Hercules is set and the GAP is initialized according to appendix D with the version 01.01.444. In the software “Gas Analyzer” the pump voltage is set on 6.25 V and the smoothing parameter on 0.2. Before the data collection starts re-initialization is necessary as the concentration plots diverge. When the plots are stable the “start data” button is pushed and the air in the climate room is pumped through the GAP throughout the test. The experiments continue for three times for approximately three minute each.

The second part of the testing is the dynamic test which follows after the static test. To simplify the inhalation, the mouthpiece is again attached to the GAP followed by a short re-initialization of the GAP with the version 01.01.444. In the software “Gas Analyzer” the pump voltage is set on 6.25 V and the smoothing parameter on 0.2. The “start data” button is pushed and the inhaled air is pumped through the GAP throughout the test for three times for approximately one minute each.

Figure 27 the left figure shows the pressure cabin and the right figure shows the setup of the GAP inside the pressure cabin.
Results

The experiments performed with two different pressures, the first one executed at 699 mbar and the second one executed at the pressure of 1060 mbar, are plotted below. The interesting part is to see how well the GAP performs during these circumstances.

Static pressure experiment

The figures below show the concentration of Nitrogen, Oxygen and Carbon dioxide plotted against real time data. The measurements where collected statically see Figure 19 in the pressure cabin.

The first figure, Figure 28 shows the concentration of air in the room plotted against real time data during a pressure of 699 mbar.

![Figure 28, pressureT1 4 with the pressure 699 mbar](image)

The average concentration of nitrogen is 75.7 % with the standard deviation of 0.77, the average concentration of oxygen is 23.0 % with the standard deviation of 1.28 and the average concentration of carbon dioxide is 1.3 % with the standard deviation of 1.73.

The second figure, Figure 29 shows the concentration of air in the room plotted against real time data during the pressure of 1060 mbar.
The average concentration of nitrogen is 76.0 % with the standard deviation of 1.33, the average concentration of oxygen is 23.0 % with the standard deviation of 1.04 and the average concentration of carbon dioxide is 0.14 % with the standard deviation of 1.10.

**Dynamic pressure experiment**

The figures below show the concentration of Nitrogen, Oxygen and Carbon dioxide plotted against the real time data. The measurements were collected dynamically in the pressure cabin.

The first figure, Figure 30 shows the concentration of breath air plotted against real time data with a pressure of 699 mbar.
The average of the top 10 concentration values of nitrogen is 77.1 % the average of the top 10 concentration values of oxygen is 24.1 % and the top average of the 10 top concentration values of carbon dioxide is 4.05 %.

The second figure, Figure 31 shows the concentration of breath air plotted against real time data with a pressure of 1060 mbar.

The average of the top 10 concentration values of nitrogen is 78.0 % the average of the top 10 concentration values of oxygen is 23.6 % and the top average of the 10 top concentration values of carbon dioxide is 3.46 %.
Sources of error
The biggest uncertainty is again the initialization of the GAP, as it was first performed when the test pressure was reached; therefore the calibration of the transducers is not correct. How big interference this is, is not possible to determine due to lack of possibility to extract other data then concentration data and real time data.

The second uncertainty is due to the fact that the pressure was not constant, and needed to be readjusted during the experiment. During the balancing of the pressure the measurements of the GAP diverged and a new restart was necessary.

The third uncertainty is the lack of streamed raw pressure data and again it is not possible to compare the pressure on the outside to the measured values from the GAP.

Discussion
What can be seen in Figure 28 and Figure 29 is that stability becomes an issue and that the noise has increased, but both pressure levels show concentration values of nitrogen, oxygen and carbon dioxide close to the expected values of air.

During the dynamic pressure experiments the concentration values of carbon dioxide are behaving predictably. The four phases in exhalation of carbon dioxide are observed in what can be described as a normal Kapnogram. The oxygen and nitrogen on other hand are noisy, see Figure 30 and Figure 31, but the concentration values are close to the expected values of air.

6.2.3 Part 3, single gas
Until now the GAP has yet not been tested during room temperature, dry air and normal pressure. Therefore this experiment will be performed during room temperature and normal pressure with the test gas containing elements of air, which can be considered as 20.96 % Oxygen, 79 % N2, 00.04 % Carbon dioxide and 0 % Argon.

First the knowledge of that the GAP works during these “normal” conditions must be established and secondly to see if the results of the experiments are depending on the concentrations closeness to the real concentration of air, or would a “different” percentage of e.g. oxygen give less accurate values? If dependence would be found
then is that a result of software issues or a structural problem with the theory of the GAP?

**Setup**

The GAP is placed on a table in the lab of Artema with the breath module, see chapter 4.6, next to it. First the “breath modules” plastic bags are filled with the chosen test gas from the gas bottles from Artema. Secondly the GAP is connected to the laptop with the software’s “Gas Analyzer”, “Hercules” and “Breath Simulator”, see Figure 32. The Hercules is set and the GAP is initialized with normal air and pressure, according to appendix D with version 01.01.499 In the software “Gas Analyzer” the pump voltage is set on 6.25 V and the smoothing parameter on 0.2. After the initialization, the breath module is connected to the GAP’s inlet via a rubber tube with the diameter of 5 mm. and in the “breath simulator” the frequency 6 breath/min is chosen. The “start data” button is pushed and the test gas is pumped, from the plastic bag with the frequency of 6 breaths per minute, through the GAP throughout the test for approximately one minute. After a minute the frequency in the breath simulator was changed to 12, 24, 48, 60 and 72 breaths per minute. During the experiments in part 3 the mouthpiece is disconnected.

![Figure 32, the setup for the GAP when connected to the breath module](image)

**Result**

In this experiment two different concentrations of oxygen are tested. The first experiment contains of 21 % oxygen balanced with nitrogen and the second experiment of 60 % oxygen balanced with nitrogen. During the experiment 6 different breath rates were applied 6, 12, 24, 48, 60 and 72 breath/min. The tests are evaluated...
with two different software’s of the Gas Analyzer i.e. version 01.01.444 and 01.01.464

21 % O₂ bal N₂ with the breath rate 6 and 72 and S/W version .444

In the first experiment 21% oxygen balanced with nitrogen is used with the breath rate 6 breath/min see Figure 33.

In Figure 33 the concentration of nitrogen should reach 70 % and the concentration of carbon dioxide should be zero when the oxygen reaches 21 %. But what can be seen in the plot above is that the concentration of nitrogen swings between 79-81 % and the concentration of carbon dioxide swings between 0.3-0.6 % and that the concentration of oxygen never reaches 21 % during the experiment. What also can be seen in the plot above is that during the 30 s, approximately 3 breaths are taken which is correct with the chosen breath frequency.

In the second experiment 21 % oxygen balanced with nitrogen is tested with the chosen breath rate of 72 breath/min see Figure 34.
Figure 34, 21% O₂ Bal N₂ with the chosen breath rate 72 breath/min
In Figure 34 the concentration of nitrogen should reach 79% and the concentration of carbon dioxide should be zero when the concentration of oxygen reaches 21%. As can be seen in the figure above the concentration of oxygen reaches as it highest 17%. The concentration of nitrogen swings between 83-86% and the concentration of carbon dioxide is negative and therefore an incorrect value. What also can be noticed is that during approximately 30 seconds, 37 breaths are taken which corresponds to the chosen breath rate of 72 breaths per minute.

60 % O₂ bal N₂ with the breath rate 6 and 72 and S/W version .444
In the third experiment, 60 % O₂ balanced with N₂ is tested with the breath rate of 6 breath/min see Figure 35 with a breath rate of 6 breath/min.
The concentration of nitrogen is almost 300% at the highest and 75% at the lowest, the concentration of oxygen is 20% at the highest and over – 200% at the lowest and the concentration of carbon dioxide is 80% at the highest and 0% at the lowest. What also can be noticed is that only five breaths are registered instead of six as the chosen breath frequency.

In the fourth experiment 60% oxygen balanced with nitrogen the breath rate is chosen to 72 breaths/min see Figure 36 with a breath rate of 72 breath/min.
In Figure 36 the concentration of nitrogen is oscillating between 300 % at the highest and 75 % at the lowest, whiteout consideration for the peaks from 2000 to -2000%. The concentration of oxygen is 20 % at the highest and around – 200% at the lowest and the concentration of carbon dioxide is dioxide is 80% at the highest and 0% at the lowest. The concentrations are similar to the concentrations in the previous experiment “60% O₂ Bal N₂ with the chosen breath rate 6”. What also can be noticed is that when the breath are calculated for the first 20 s there are 25 breaths, which sums up to 75 breath per minute which is 3 breath more than the chosen breath rate of 72 breath per minute.

**21 % O₂ Bal N₂ with the breath rate 6 and 72 and S/W version 02.01.464**

The fifth experiment with 21% oxygen balanced with nitrogen with the chosen breath rate of 6 and the S/W version 464 can be seen in Figure 37.

In Figure 37 the concentration measurements are closer to the expected values, i.e. the concentration of nitrogen is oscillating between 81-79 % and the concentration of oxygen is oscillating between 22-19 %. The concentration of carbon dioxide is incorrect as the concentrations oscillates between -0.2 % and -0.6%. It is hard to distinguish the chosen breath frequency of 6 breaths per minute in the figure.
The sixth experiment with 21% oxygen balanced with nitrogen with the chosen breath rate of 72 and the S/W version 464 can be seen in Figure 38.

![Graph showing concentrations of nitrogen, oxygen, and carbon dioxide over time.](image)

In Figure 38 the concentration of nitrogen is oscillating between 82-79 %, the concentration of oxygen is mainly oscillating between 20-19 % and the concentration of carbon dioxide oscillates between 0 % and -0.4 %. In this figure it is also hard to distinguish the breath rate.

**60 % O₂ bal N₂ with the breath rate 24 and 72 and S/W version .464**

In the seventh experiment with 60 % oxygen balanced with nitrogen the breath rate 24 is chosen and the S/W version 464 and can be seen in Figure 39.
In Figure 39 the concentration values are close to the expected values, i.e. when the concentration of nitrogen is 40 % the concentration of oxygen is 60 % and vice versa. The expected concentration of carbon dioxide should be zero during the experiment, but oscillates between 0 % and -1 %. For the first 10 s, 4 breaths are taken which is correct as the breath rate is chosen for 24 breaths per minute for this experiment.

The eighth experiment, with 60 % oxygen balanced with nitrogen with the chosen breath rate 72 breaths/min with the S/W version 464, can be seen in Figure 40.
If a higher breath rate than 24 is chosen, as in this experiment see Figure 40, the system reacts too slowly and the concentration of nitrogen oscillates between 68 % and 54 %, the concentration of oxygen only rises up to approximately 50 % instead of 60 % and the carbon dioxide oscillates between 0.3% and -0.6%.

**Sources of error**

In the version 02.01.464 the sampling of data is increased from the sensors and transducers in the GAP which also makes the system slower compared to the earlier versions of the software.

**Discussion**

In the two experiments with 21% $O_2$ balanced with nitrogen with the software version 444 the chosen concentration of nitrogen and oxygen is close to the chosen test gas. Both breath frequencies are correct in the figures, but in the experiment with the chosen breath frequency of 72 the system is not fast enough as the concentration values are not reaching the expected values.

In the two experiments with 60% $O_2$ balanced with nitrogen with the software version 464 the chosen test gas-mixture is not close to the normal concentrations of air. This generates complications as the results from the GAP are incorrect.

In the two experiments with 21% $O_2$ balanced with nitrogen with the software version 464 the breath frequency becomes hard to distinguish as the results are noisy. Compared to the same experiment with the software v 444 this system is slower and noisier.

In experiments “60 % $O_2$ balanced with nitrogen with the software version 464” the concentrations values of nitrogen and oxygen are correct see Figure 39. The noise is minimal and the figure shows clearly that when breath frequency is on, the oxygen level reaches 60 % and the nitrogen reaches 40 %. When breath module is off, the oxygen level is approximately 21 % and nitrogen is approximately 79 %. What is important to notice is the fact that the carbon dioxide is still negative and that after the chosen breath frequency of 24 breaths per minute the system becomes too slow, which is why the concentration values are not reaching the expected values.
6.2.4 Part 4, gas-mixture

As the last part of the experiment of the GAP the idea was to test gas mixtures containing anesthetic gases and alcohol together with air. The software gained from the external partner is written for handling only air and elements of air. During the previous experiments there is still one that has not been executed, i.e. breath-air during room temperature and atmospheric pressure.

Setup

The GAP is connected to a computer with the software’s Hercules and Gas Analyzer. The mouthpiece is connected as the first test will be executed dynamically, see Figure 20. The Hercules is set, and the GAP is initialized according to appendix D with normal air and pressure with software version 444. In the software “Gas Analyzer” the pump voltage is set on 6.25 V and the smoothing parameter on 0.2. After the initialization the “start data” button is pushed and the air is pumped through the GAP throughout the test for three times for approximately one minute each.

For the second dynamic experiment the GAP is re initialized with normal air and pressure with the software version 464. The pump voltage is set on 6.25 V and the smoothing parameter on 0.2 in the software “Gas Analyzer”. After the initialization the “start data” button is pushed and the air is pumped through the GAP throughout the test for three times for approximately one minute each.

In the third test the mouthpiece is disconnected and instead the breath module is used, see Figure 32. Before starting the initialization the breath modules plastic bags are filled with the gas-mixture of 5 % CO₂, 40 % O₂ balanced with nitrogen and connected to the breath module. The Hercules is set and the GAP is initialized with normal air and pressure according to appendix D with the software version 01.01.464. In the software breathe simulator the breath frequency is set on 6 breaths per minute. After initialization with the pump voltage 6.25 V and the smoothing parameter 0.2, the “start data” button is pushed, before the breath module is connected to the GAP via a five mm cable. The test gas from the breath module is pumped through the GAP throughout the test for approximately 3 minutes.
**Result**

In the first experiment the GAP is tested dynamically during room temperature and atmospheric pressure with the S/W version 444, see Figure. During the experiment faster breathing is followed by slower breathing see Figure 41.

![Breath air version 444](image)

During the first 20s in Figure 41 the breathing is fast with a breath rate of approximately 36 breaths per minute. The concentration of nitrogen is oscillating between 80 % and 70 %, the concentration of oxygen is oscillating between 27 % and 20 % and the concentration of carbon dioxide is oscillating between 2 % and 0 %.

After 30 ms the breathing is slower with a breath rate of approximately 12 breaths per minute. The concentration of nitrogen is oscillating between 78 % and 74 %, the concentration of oxygen oscillates between 24 % and 22 % and the concentration of carbon dioxide oscillates between 3 % and -0.5 %.

In the second experiment see Figure 42 the GAP is tested dynamically with room temperature and atmospheric pressure with the S/W version 464.
During the first 30 seconds the breath is slow with a breath rate of approximately 6 breaths per minute. The concentration of nitrogen is oscillating between 82 % and 76 %, the concentration of oxygen is oscillating between 23 % and 16 % and the concentration of carbon dioxide is oscillating between 2 % and 0 %. During the last 30 seconds the breath rate is approximately 18 breaths per minute. The concentration of nitrogen is oscillating between 83 % and 71 %, the concentration of oxygen is oscillating between 27 % and 16 % and the concentration of carbon dioxide is oscillating between 3 % and -1 %.

In the last experiment, see Figure 43, the setup is changed, the breath modules plastic bags, see chapter 4.6, are filled with test gas consisting of 40% oxygen and 5 % carbon dioxide and the breath rate is chosen to 6 breaths per minute. The software version 444 is used in this experiment.
The concentration of nitrogen, oxygen and carbon dioxide are not even close to the expected concentration of 35 % nitrogen, 40 % oxygen and 5 % carbon dioxide, see Figure 43. The experiment is executed three times, but comparable concentrations where gained. The breath rate is incorrect as maximum 4 breaths per minute are registered instead of the chosen breath rate 6 breaths per minute.

**Sources of error**

The breaths are made by a person with asthma, which is a disease that causes narrowing of the airways. Therefore the exhalation in the experiments might be reduced. As there has not been any comparison between a person with normal functioning lungs and an asthmatic the amount of reduction is unknown.

**Discussion**

It is interesting to see the results of the first two experiments in part 4 as the software was written for just these types of experiments, i.e. breath air during normal pressure and temperature. During the slow breathing in Figure 41 the breath frequency of nitrogen and oxygen are hard to distinguish, which can depend on the lack of measurement data. The carbon dioxide is reaching values below zero which is not acceptable. In Figure 42 the breath rate of nitrogen and oxygen are visible, but the carbon dioxide reaches concentration values below zero. To change the pump voltage or the smoothing parameter was of no help as the software crashed during the procedure.
Chapter 7 Discussion

A fully functional apparatus with enormous potential is the impression gained after reading the reports of Tadeusz M. Drzewiecki. The anticipations was therefore high during the experimental part of the work where the GAP was exposed to temperature and humidity test, pressure test and test gases containing different concentrations of nitrogen, oxygen and carbon dioxide. In early stages of analysis awareness of the insufficiency of the software became clear. With a software prototype lacking important functionalities and tracing possibilities the knowledge of GAP’s hardware performance diminishes.

Another immense limitation during the thesis is that there is no information to be found of the geometrical properties of the micro-fluidic sensor, which is the skeleton in the four bulk equations. The micro-fluidic sensor that includes the micro-fluidic oscillator generates the measurements for the flow calculation. The same flow rate value is then used to determine both density and viscosity. Even though geometrical assumptions are made it becomes an error source.

Despite the fact of the complications with the software, lack of geometrical variables and incorrect initialization the functionality of the GAP is proven. For example the results in the temperature and humidity test and pressure test, gained with the software version 444, shows concentration values of air close to the expected values of air regardless of the error sources. With the software version 444, the chosen breath rate is measured but other concentrations of nitrogen, oxygen and carbon dioxide than the concentrations of air can not be determined. With the software version 464 the sampling frequency is increased. Now other concentrations of nitrogen, oxygen and carbon dioxide than air can be determined but when the chosen breath rate exceeds 24 breaths per minute the system is too slow to handle the values correctly.

When it comes to the principle of the GAP, which was discussed in chapter 3, there are still many unanswered questions. At the moment the accuracy of the experiments can not be determined but the question whether or not there is a possibility to improve the results needs to be discussed. By excluding the laminar part in equation (3.7) and the turbulent part in equations (3.15) the accuracy diminishes such a grade that the
concentrations cannot be determined. Most likely the independent bulk equations are not used, instead higher order equation such as equation (4.1) and equation (4.2) are used to get more accurate concentration values. To use the high order equation is not without risk and problems can occur as can be seen in the Figure 35. The impression gained from the figure is that there is problems with the optimization. When the concentration of nitrogen, oxygen and carbon dioxide is not in close proximity to the concentration found in air the outputs are completely wrong. When the software version 444 was changed to version 464 other concentration of nitrogen, oxygen and carbon dioxide than the levels in air can be determined but on the expense of the rapidity of the system. The difficulty will be the balance between high sampling frequency and accuracy against the rapidity of the system. For this further work is needed.
Chapter 8 Conclusions

Innovative cost effective technology, with the ability to extract concentrations in any gas-mixture in real time, gives the GAP a head start on the today’s market if functionality can be proven. The expectations are therefore high on the GAPs performance and the main focus of this thesis has been to answer the question whether or not the GAP works.

The answer to that question is yes, the GAP works. As can be seen in the experiment “60 % O₂ balanced with N₂ with the breath rate 24 and 72 and S/W version .464” both the concentration of nitrogen and oxygen coincides with the expected concentration values of the test gas. The noise is negligible and the system is fast enough. The remaining results of the experiments show that at this moment in process it is not possible to neither use other test gases than constituents of air for experiments nor determine the accuracy of the extracted data, due to uncompleted software and the dimension of the error sources.

The GAP comes across as an apparatus with no real area of use as its only application at the moment is to calculate the concentration of air. What is important to understand is that the concentration of air consists of three different molecules that in theory could be any other three molecules. The reason for the test gas only being air is the fact that the software has no library containing the thermodynamic constant of other gases needed in the bulk equations. This neither proves nor disapproves the GAP abilities but lets the reader know that there is need for further software development and testing to truly acknowledge the GAPs potential.

In chapter 3 the discussion revolves around the validity of the structure i.e. whether or not it is possible to determine the concentration of the gas mixture with the independent bulk equations. To be able to provide definitive answers, faultless software with the ability to extract analog data is necessary, which we do not have. What can be seen in the results from the experimental part of the thesis is that the concentration values of nitrogen, oxygen or carbon dioxide are frequently negative. The conclusion drawn is that the equation 3.7 and 3.15 are not adequate therefore the dependent equations 4.1 and 4.2 are used as an optimization and consequently the
summation of the concentrations in the fourth bulk equation, 3.17, does not add up to 100 percent.

There is a future for the GAP as can be seen in the experimental parts but it is not yet a complete product and further work is needed. Firstly software written in-house is a must and secondly more experiments are necessary before accuracy of the GAP can be determined and to answer the question of how well the GAP does work.
Chapter 9 Continued Effort

As there are many different variables missing the best way of testing the GAP would be to start with and CAD simulation program. For an example COMSOL could be used to draw the micro-fluidic sensor. It is important to have the dimensions of the micro-fluidic sensor to reduce the error sources. Also COMSOL can illustrate the turbulence and laminar part in the orifice and capillaries so knowledge about dependence can be sorted out. When the dimensions are drawn and tested in the program the step to building an own micro-fluidic sensor is not far away.

The need of raw sensor data is fundamental for the ability to evaluate the GAP properly. During testing the only data gained was time and concentration of the gases leaving gaps in the understanding and troubleshooting. To be able to show that the GAP has an accuracy of 0.5 % it is important to troubleshoot the code to make sure no logical error are made, all transducers are working and, the ability to extract wanted analog data and to ensure that the balance between the sample rate and the rapidity of the system is optimized.

To minimize the error sources the experimental part should use test gas containing one element of air, i.e 100 % nitrogen or 100 % oxygen. The experiments should also be executed statically during normal temperature and pressure. After one element has been tested, two elements of air can be tested statically during room temperature and normal pressure and so on.

The GAP has potential but to be able to evaluate the apparatus correctly the proposals made in this chapter are necessary.
Chapter 10 References


[26] Illustration of a capillary, Available in “Fundamentals of fluid mechanics” Figure 6.30


Appendix A

%Geometrical calculations of the orifice and the capillaries in the micro-fluidic sensor.

%Geometry of the capillaries
k1=2.5*10^13;
k2=4.4*10^12;

% hc=bc == square.
d_cap=sqrt(sqrt(1/(2*k2)));       %[m] The diameter of the capillaries
L_cap= d_cap^4*k1/(12*5/2);       %[m] The length of the capillaries

%Geometry of the orifice
k3=1.5*10^12;
k4=6.27*10^13;

%hc=bc == square.
d_ori=sqrt(sqrt(1/(2*k4)));       %[m] The diameter of the orifice
L_ori=d_ori^4*k3/(12*5/2);        %[m] The length of the orifice
Ad_ori=d_ori^2;                  %[m^2] The

%Geometry of the acoustic transmission line
D=1.8*10^-3;
AD=pi*D^2/4;                     %Area of a circle [m^2]

% The dimensionless constants k1, k2, k3 and k4 are gained from the MathCad file “4 Gas Analyzer CRIT VISC CALC AND TIME TRACE GASSES”
Appendix B

%Reynolds number----------------------------------------------
Ra_air=1.205;       %[kg/m^3]
My_air=1.511*10^-5    %[m^2/s]

Re_ori_d=[];
Re_cap_d=[];

Q=(0.05:0.001:0.120)/60000;%The chosen flow
i=1;

% How the reynolds number changes when the flow is changed
for i=i:length(Q)

    % Reynolds number - Orifice
    A_ori=d_ori^2;
    v_ori=Q(i)/A_ori;
    Re_ori_d(i)=Ra_luft/My_luft*v_ori*d_ori;

    %Reynolds number-Capillary
    A_cap=d_cap^2;
    v_cap=Q(i)/A_cap;
    Re_cap_d(i)=Ra_luft/My_luft*v_cap*d_cap;
Appendix C

%independent_viskosity

%http://www.engineeringtoolbox.com/air-properties-d_156.html

%Constants-------------------------------------------------------------

%Viscosity for air
My_air=1.511*10^-5;  [%m^2/s]

%Density for air
Ra_air=1.205;   [%kg/m^3]

%Molar mass
M_air=28.95;   [%kg/mol]

% Capillary
k1=2.5*10^13;
k2=4.4*10^12;

 d_cap=5.8060e-4;   [%m]
 L_cap=0.0947;   [%m]
 A_cap=3.3710e-7;   [%m^2]

%Orifice
k3=1.5*10^12;
k4=6.27*10^13;

 d_ori=2.9883e-4;   [%m]
 L_ori=3.9872e-4;   [%m]
 A_ori=8.893e-8;   [%m^2]

%--------------------------------------------------------------------

%Differential pressure change in the capillaries due to change in the flow

dP_cap=[];
dP_cap_lam_and_turb=[];
i=1;
Q_cap=(0.04:0.001:0.086)/60000;
N=11;
R=8.314; % [J/mol*K] allmänna gaskonstanten;
for i=i:length(Q_cap)
    %Differential pressure calculated with the equation 2.13
    dP_cap(i)=(11*8*L_cap*My_air*Q_cap(i))/(pi*(d_cap)^4);

    %Differential pressure calculated with the equation 3.2
    dP_cap_lam_and_turb(i)=k1*My_luft*Q_cap(i)+k2*Ra_air*Q_cap(i)^2;
end
figure(1)
plot(Q_cap,dPc,'b',Q_cap,dP_cap_lam_and_turb,'g')
xlabel('Flow Q [m^3/s]')
ylabel('Pressure diference dP_cap [Pa]')
title('Differential pressure with and without the turbulent part ')

text(1.15*10^-6,400, '\leftarrow dP laminar + turbulent')
text(0.85*10^-6,400, 'dP laminar \rightarrow')

%------------------------------------------------------------------
%Differential pressure change in the orifice due to change in the flow

dP_ori=[];
dP_ori_lam_and_turb=[];
j=1;
Q_ori=(0.04:0.001:0.086)/60000;

for j=j:length(Q_ori)
    %Differential pressure calculated with the equation 2.5
    dP_ori(j)=1/2*(1/Ad_ori^2-1/AD^2)*Ra_luft*Q_ori(j)^2;
    %Differential pressure calculated with the equation 3.1
    dP_ori_lam_and_turb(j)=k3*My_luft*Q_cap(j)+k4*Ra_luft*Q_cap(j)^2;
end

figure(2)
plot(Q_ori,dP_ori,'r',Q_ori,dP_ori_lam_and_turb,'black')
xlabel('Flow Q [m^3/s]')
ylabel('Pressure difference dP [Pa]')
title('Differential pressure with and without the laminar part')
text(1.15*10^-6,100, '\leftarrow dP turbulent')
text(0.7*10^-6,100, 'dP laminar + turbulent \rightarrow')
Appendix D

DRT, Inc. Gas Analyzer
User’s Guide

December 15, 2008

Introduction

This document is a reference guide for usage of the DRT, Inc. Gas Analyzer system. The system is comprised of a data acquisition hardware, PC-based analysis software, and accessories. A detailed list is included:

- Data Acquisition Unit
- Installation CD
- IEC C13 mains power cord
- RS-232 Serial Communications Cable
- Microline sample tube & Airway adapter
- HUMID-VENT™ heat and moisture exchanger

System Requirements

- Operating System: Microsoft Windows XP w/Service Pack 2
- CPU: 2.00 GHz
- RAM: 512 MB
- (1) RS-232 COM Port
- 120 Volt 60 Hz AC Power Supply
Hardware Installation

Hardware installation is quite simple since there are only three connections. Connect the mains cord to the power entry module on the back of the data acquisition unit (see Figure 1). Ensure that the I/O switch is switched to 1.

Figure 1: Power Connection

Next, connect the RS-232 serial communications cable to the RS-232 ports on both the data acquisition unit rear panel (see Figure 2) and the PC.

Figure 2: Serial Connection
Finally, the microline sample tube must be connected to the front panel sample input (see Figure 3). Also, the heat and moisture exchanger should be inserted in to the airway adapter during respiratory analysis.

![Sample](image)

Figure 3: Sample Line Connection

**Software Installation**

The software can be installed on a PC by simply copying the bin directory from the installation CD to a local folder. The main application file is **DRTCondAnalyzer.exe**. All dependencies are included in the same directory and no system installation is necessary.

**User Settings**

The software settings are located in the Settings folder. A set of INI files are provided to allow the user to modify multiple settings. These files are loaded at boot-up and the application must be restarted for the changes to take effect. Most settings will not need to be adjusted. However, the COM port for the PC defaults to COM1 and may be need to be changed to match the PC’s port number. This setting can be found in the **Program Data.ini** file:

```ini
[ Program ]
Port = COM1
```
Initialization

The main power switch is located on the data acquisition unit front panel. Once the unit is switched on, the red Power LED will light indicating power and the green Ready LED will flash green indicating the data acquisition software is operational. To perform gas analysis, execute the application on the PC, DRTGasAnalyzer.exe. The Control Panel (see Figure 4) is located on the left-hand side of the application. Initiate data by pressing the Start Data button. The left Status LED will display yellow indicating initialization and the right Status LED will flash green indicating data flow from the data acquisition unit. Once, the unit has initialized the left Status LED will display red and the data acquisition pump will engage. After initialization, the unit must be given a minimum 10 minute warm up period from a cold start. After the necessary warm up period, press the Rezero button to self calibrate. During the Rezero process for respiratory analysis, only dry air must be allowed to flow into the sample line. Subsequent to Rezero, the unit is ready for gas analysis.

![Figure 4: Control Panel](image)

4
Display

Figure 5 illustrates the display of each concentration solution versus time in a dockable window. These windows can be moved, resized, and tabbed by the user for a convenient, custom display layout.

![Figure 5: DrtGasAnalyzer Display](image)

Diagnostics

The Control Panel contains a radio button to enable/disable a monitor window (Figure 6) for displaying some of the intermediate calculations. This window is useful for diagnostic purposes and should remain hidden for normal operations.
Additional Controls

The Control Panel also contains three additional controls for customizing the gas analyzer:

- Pump Voltage
- Smoothing Parameter
- Property Mode

The Pump Voltage slider provides the user with real-time control of the gas flow through the pump voltage. Similarly, the Smoothing Parameter slider provides the user real-time control over the smoothing of the input data from the data acquisition system. A lower number corresponds to more smoothing, and consequently, slower response time. Lastly, the Property Mode radio buttons select between 2- (3 gases) and 3-propert (4 gases) analysis mode.

Logging

A logging feature is included and can be customized from parameters included in Program Details:

[Program J]
Logging Ip Address = 127.0.0.1
Daq Data Logging Port = 7755
Mixture Properties Logging Port = 7755
Concentrations Logging Port = 7755
Logging Significant Digits = 5

The logging protocol is a UDP socket-based format containing commas separated
ASCII text. A third-party client can be used to stream the data to a file for post-processing or directly into another application, in real-time. For instance, Matlab’s Instrument Control Toolbox™ includes a UDP object that enables direct import into a Matlab workspace.

The DAQ data logging format is detailed below:
<Timestamp hh:mm:ss.xxx>, <Packet Id>, <Internal Packet Id>, <Board Address>, <Internal Timestamp>,
<Fifo Count>, <Voltage #1>, <Voltage #2>, <Voltage #3>, <Voltage #4>, <Voltage #5>,
<ETD Current>, <Frequency>, <THI>, <TL2>, <DAC #1>, <DAC #2>, <Pot>, <CR><LF>

The mixture properties logging format is detailed below:
<Timestamp hh:mm:ss.xxx>, <Packet Id>, <Qp>, <Cv>, <Gama>, <P>, <Q>, <Rho>, <CR><LF>

The concentration logging format is detailed below:
<Timestamp hh:mm:ss.xxx>, <Packet Id>, <Gas #1>, <Gas #2>, <Gas #3>, <Gas #4>, <CR><LF>
## Appendix E

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