DESIGN OF A NON-DISPERSIVE INFRA-RED (NDIR) BASED CO_2 SENSOR TO DETECT THE HUMAN RESPIRATORY CO_2

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DEDICATION

This thesis is dedicated to my beloved parents, elder brother, supervisor, lecturers and friends for their countless love, support and huge encouragement and prayers throughout the journey. Furthermore, I would like give my gratitude to my supervisor because this work would not be possible to finish without her constant support.

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ABSTRACT

Respiratory Carbon dioxide (CO_2) contains substantial amount of information that can be used to diagnose and treat pulmonary diseases. Many devices have been developed for this purpose, such as capnography, vital monitor, peak flow meter, spirometer etc. There are many CO_2 sensor are available in the market but among them NDIR based sensors are considered to be most inexpensive with its accuracy in terms of sensitivity and fast response time. There are commonly two types of technology available for detection; mainstream and sidestream. Mainstream technology is preferable than sidestream because sidestream is not applicable in intubated patients and at the same time it tends to give delay in detection due to longer transmission tube. Most of the NDIR CO_2 sensor are being used for the environmental CO_2 detection and there are very few mainstream NDIR based CO_2 sensor are available in the market. These sensor have a vast number of advantages with some disadvantages as well; such as high response time, thermal noise, temperature increase and others. This project proposed the specification of the electrical circuit of the NDIR CO_2 sensor combined with a gas chamber to detect human respiratory CO_2. To determine the specification of the CO_2 sensor circuit, the components value has been calculated and then the circuit design has been carried out by using Multisim Software. The overall CO_2 sensor circuit has six circuit blocks named oscillator, driver circuit, preamplifier, voltage regulator, rectifier, LPF and each of the blocks were built and simulated in the Multisim software. After the simulation the circuit has been built on breadboard to test the output. An IR source from International Light Technologies (ILT) 4115-2A and pyroelectric photodetector L2100X2020 from laser component were used for this project as NDIR components. After the successful simulation from breadboard a gas acquisition cell has been designed to acquire the human CO_2 gas. The design has been done by using Solid Works software and printed from a 3D printing machine. The material used for this chamber was ABS. After placing all the calculated components with the source and detector the output has been observed on the digital oscilloscope as a capnograph wave form showing the voltage range. These waveforms are being used in a capnometer determining respiratory diseases. The circuit shows a response time of 6 second with less noise and the waveform showed clear view of detected CO_2 without any temperature increase.

ABSTRAK

Karbon dioksida pernafasan (CO_2) mengandungi banyak maklumat yang dapat digunakan untuk mendiagnosis dan merawat penyakit paru-paru. Banyak peranti telah dibangunkan untuk tujuan ini, seperti capnography, monitor penting, meter aliran puncak, spirometer dan sebagainya. Terdapat banyak sensor CO_2 yang terdapat di pasaran tetapi di antara mereka sensor berdasarkan NDIR dianggap paling murah dengan ketepatannya dari segi sensitiviti dan masa tindak balas yang cepat. Terdapat dua jenis teknologi yang sedia ada untuk pengesanan; arus perdana dan sidestream. Teknologi arus perdana lebih baik daripada sidestream kerana sidestream tidak boleh digunakan dalam pesakit yang diintubasi dan pada masa yang sama ia cenderung memberi keterlambatan pengesanan kerana tiub transmisi yang lebih lama. Kebanyakan sensor NDIR CO_2 digunakan untuk pengesanan CO_2 alam sekitar dan terdapat sangat sedikit aliran utama NDIR sensor CO_2 yang terdapat di pasaran. Sensor ini mempunyai sejumlah kelebihan dengan beberapa keburukan juga; seperti masa tindak balas yang tinggi, bunyi terma, kenaikan suhu dan lain-lain. Projek ini mencadangkan spesifikasi litar elektrik sensor NDIR CO_2 yang digabungkan dengan ruang gas untuk mengesan CO_2 pernafasan manusia. Untuk menentukan spesifikasi litar sensor CO_2, nilai komponen telah dikira dan kemudian reka bentuk litar telah dijalankan dengan menggunakan Perisian Multisim. Litar sensor CO_2 keseluruhan mempunyai enam blok litar yang dinamakan pengayun, litar pemacu, preamplifier, pengawal selia voltan, penerus, LPF dan setiap blok dibina dan disimulasikan dalam perisian Multisim. Selepas simulasi litar telah dibina di atas papan roti untuk menguji output. Satu sumber IR dari International Light Technologies (ILT) 4115-2A dan photodetector pyroelectric L2100X2020 dari komponen laser telah digunakan untuk projek ini sebagai komponen NDIR. Selepas simulasi yang berjaya dari papan roti sel pengambilalihan gas telah direka untuk memperoleh gas CO_2 manusia. Reka bentuk telah dilakukan dengan menggunakan perisian Solid Works dan dicetak dari mesin pencetak 3D. Bahan yang digunakan untuk ruangan ini adalah ABS. Selepas meletakkan semua komponen yang dikira dengan sumber dan pengesan output telah diperhatikan pada osiloskop digital sebagai bentuk gelombang capnograf yang menunjukkan julat voltan. Bentuk gelombang ini digunakan dalam capnometer yang menentukan penyakit pernafasan. Litar ini menunjukkan masa tindak balas 6 second dengan bunyi kurang dan bentuk gelombang menunjukkan paparan jelas CO_2 yang dikesan tanpa peningkatan suhu.

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LIST OF ABBREVIATIONS

CO_2	-	Carbon Dioxide
MIR	-	Mid Infrared
LED	-	Light emitting diode
NDIR	-	Non-dispersive infra-red
Volt	-	Voltage
ICU	-	Intensive care unit
CAD	-	Computer Aided Design
3D	-	Three-Dimensional
UTM	-	Universiti Teknologi Malaysia
PWM	-	Pulse Width Modulation
ANN	-	Artificial Neural Network
UART	-	Universal Asynchronous Receiver/Transmitter.
PPM	-	Parts per meter
COPD	-	Chronic obstructive pulmonary disease
DSO	-	Digital signal oscilloscope
DC	-	Direct current
LPF	-	Low pass filter
HPF	-	High pass filter
BPF	-	Band pass filter
ILT	-	International Light Technologies
ABS	-	Acrylonitrile butadiene styrene
CM	-	Current Mode
VM	-	Voltage Mode
IR	-	Infrared
O_2	-	Oxygen
Cm	-	Centimetre
mA	-	Milliamps
mm	-	Millimetre
mV	-	Millivolt
mW	-	Milliwatt

ms	-	Millisecond
mHz	-	Milli Hertz
Hz	-	Hertz
L	-	Length
D	-	Diameter
C	-	Concentration
A	-	Absorbance
I	-	Intensity of light striking the photodetector
I_0	-	Intensity of light of an empty sample chamber
μF	-	Micro Farad
nF	-	Nano Farad
GND	-	Ground
V_{in}	-	Input Voltage
V_o	-	Voltage
VCC	-	Positive Supply Voltage
VEE	-	Negative supply Voltage
F_c	-	Cut off frequency
N	-	No
Y	-	Yes
NS	-	Not specified

LIST OF SYMBOLS

α	-	Molar absorption co-efficient
μ	-	Micro
Ω	-	Ohm
Π	-	pi
λ	-	Lamda
±	-	Plus minus sign
≤	-	Less than or equal to
≥	-	Greater than or equal to

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CHAPTER 1

INTRODUCTION

This chapter highlights the introduction to the topic related to respiratory CO_2 including discussion on the statement of the problem, the objectives of this research, the scope of this research work and its significance and finally the thesis organization.

1.1 Background of the Study

The goal of the research is to design a 'Non-Dispersive Infra-Red (NDIR) based CO_2 Sensor to Detect Human respiratory CO_2'. There are different designs had been done and tested for CO_2 sensor. It is very important to choose the right design and components for building a CO_2 sensor for medical application. In NDIR based design, the selection of source, detector, design of gas chamber and the material selection of the gas chamber plays vital role to get the correct output of the sensor device. In this design, the components were selected in a manner to detect the CO_2 gas correctly. NDIR based sensors considered to be most inexpensive with high accuracy therefore this technology were preferable to design a new sensor with this technology. This design can be considered as a novel gas sensor because the specified circuit design and the selected electronic components used in this design had not been used by any other researcher to implement NDIR sensor.

Respiration is an important physiological process which can maintain the vital signs of people stability. Respiratory diseases, such as asthma, chronic rhinosinusitis, bronchiectasis and obstructive sleep apnea are widely prevalent all around the world. To effectively and accurately assess cardio respiratory functions, respiratory monitoring is the key component during the administration of respiratory diseases and intensive care unit [7, 8]. In this work, the designing section of the NDIR sensor is focused which can be used for detecting CO_2 gas only called single channel CO_2 sensor. The concentration of gas in normal exhaled human breath is around 35,000 ppm to 50,000 ppm, which is corresponds to a sea level partial pressure of 26.6 to 38.0 mmHg. It is roughly a factor of 100, higher concentration between inspiration and expiration and CO_2 gas is fairly straight forward to measure [9].

In this work, the sensor circuit designed with mainstream system where the sensor can directly detect the gas and pass it for further processing. Typically, the main components of NDIR are infrared sources (lamps), sample chambers (or light tubes), wavelength filters, and infrared detectors [5]. An infrared ray is radiated onto the respiratory gas from a light-emitting element. A Voltage corresponding to the amount of light which is absorbed by CO_2 contained in the respiratory gas is detected by a light-receiving element, thus detecting the CO_2 [12].

1.2 Problem Statement

Many optical sensor offer high resolution, but can be very expensive depending on the quality of the light source, optical system and the detector used [13]. Most of the NDIR sensors are made for industrial use or environmental CO_2 detection and that is not suitable for respiratory CO_2 detection. As the CO_2 sensors are also being used in medical device therefore NDIR sensors are preferable for medical devices due to its reliable results and a lot of researches are going on this topic. There are two types of technology for detection, one is mainstream and another one is sidestream. Mainstream technology considered better than sidestream technology due to its sensitivity, high response time, no samples removed from breathing circuit and compatibility with intubated patients. Sidestream technology is not applicable to intubated patients and there is huge possibility of tube clogging and delaying of the delivery of CO_2 to sensor location [14]. The NDIR based mainstream CO_2 sensors are not widely available in the market and the available sensors have number of disadvantages likely delay in output, high initializing time, high warm-up time, temperature increase and most importantly noise.

To overcome the problems related to NDIR sensors this study is proposing an electrical design of sensor that is capable to detect the CO_2 using mainstream technology and can be used in any device for respiratory CO_2 detection in future.

Most of the NDIR sensor shows temperature increase due to the thermal detector. To overcome that problem this study is proposing the design along with the component selection which is capable to show less noisy waveform without any physical temperature increase.

For NDIR technique the gas chamber plays a vital role, with the gas chamber the detection of respiratory gas is more accurate. The researches under NDIR spectroscopy poses number of limitations due to the gas chamber. Some of them are having a longer path length or very complex pathlength and also material is another issue related to gas chamber. Complex path length gives incorrect output with delay in detection. Therefore this study is proposing a design of gas chamber which is easy to construct with simple detection pathlength that may overcome the problem related to gas chamber.

1.3 Objectives

The objectives of this proposed work are-

1. To develop an electrical circuit and to simulate circuit diagram of NDIR based CO_2 sensor using Multisim software
2. To build the circuit in breadboard to test the output of the NDIR CO_2 sensor
3. To design the absorption gas chamber for detection of respiratory CO_2

1.4 Scope of Study

The assessment of this sensor circuit is focus on only CO_2 gas detection because this gas is mostly used in the medical devices for monitoring and diagnosing the respiratory diseases. This type of sensors are typically called single channel CO_2 sensor. Single channel sensors are simple and gives results with accuracy. The detector is compiled with TFC therefore the circuit doesn't show ant temperature increase during detection and because of current mood model, the output remain stable with low noise. In this study, the circuit designs has been done by using Multisim software and the gas chamber design by using solid works software. The output from the breadboard has been received and observed from the DSO which comes in voltage range. This is the typical output range of any CO_2 sensor available in the market. Though this sensor circuit gives result with accuracy as it is using a single channel detector and a source with exactly 4.26μm radiation output but still this study poses number of limitations. The output has been traced directly from breadboard where it poses unnecessary noisy signal. For this very advanced signal processing required and a PCB is required to have a robust circuit and stable output. On the other hand, the length of the gas chamber may give delay due to longer pathlength and also the material can be replaced with metal or a reflective pathlength may allow the radiation to reflect more. In this work, the gas chamber has been done with ABS and without any reflective path therefore there is no additional reflection inside the pathlength.

1.5 Significance of the Study

The need for this research is raised because in order to develop a medical device (capnometer) the selection of CO_2 sensor is very important as it needs to be appropriate with the application, monetary value, accuracy, and sensitivity. This proposed research will contribute to the existing knowledge significantly and would play a pivotal role in making better human respiratory CO_2 sensor. This project proposed an electrical circuit design of a sensor based on NDIR spectroscopy technique because it is considered to be very low cost but very sensitive with respect to other available sensors. The use of infrared technology in this study will improve the detection of CO_2 gas. Now a days the infrared technology is the most popular studies and this study is also based on it because of it reliable results. In this study, a Pyroelectric photo detector will be used which has a built in optical filter that blocks all the infrared except the radiation of 4.26 μm which is the most useful wave length to detect the CO_2 gas. The application L2100X2020 on NDIR spectroscopy will reduce the thermal noise in a great extent. Because this detector is integrated with TFC which reduces the noise and attenuates the tendency towards natural oscillation with longer amplification. The detection of CO_2 gas reveals the problem associated with heart or lung, CO_2 gas detection is also needed during emergency monitoring and delivering the anaesthesia [24, 25].

1.6 Thesis organization

This thesis consists of 5 chapters. Chapter 1 is an introductory chapter. It presents the background of the study, problem statement, objectives, scope and significance of this research work.

Chapter 2 is literature review and provides brief reviews to the number of topics. Existing CO_2 sensors, explanation of NDIR gas sensors and summary of the studies related to NDIR technique and the materials for gas cell has been carried out extensively, emphasizing on the finding as well as their limitations.

In Chapter 3, the circuit design used to achieve the aforesaid objectives has been described in detail ranging from designing hardware to software as well as from designing project PCB to gas acquisition chamber.

Results and their discussion obtained through this research project have been carried out in Chapter 4.

Conclusively in Chapter 5 summary of the whole work is given including the recommendation for the further research has been presented briefly.

REFERENCES

[1] Mason, H., et al., *Cardiovascular and Respiratory Effect of Yogic Slow Breathing in the Yoga Beginner: What Is the Best Approach?* Evidence-Based Complementary and Alternative Medicine, 2013. **2013**: p. 7.

[2] Stephenson, M., *Chapter 3 - Capturing Carbon Dioxide*, in *Returning Coal and Carbon to Nature*. 2013, Elsevier: Boston. p. 45-62.

[3] Park, H. and D. Han, *The effect of the correlation between the contraction of the pelvic floor muscles and diaphragmatic motion during breathing.* Journal of Physical Therapy Science, 2015. **27**(7): p. 2113-2115.

[4] http://antranik.org/wp-content/uploads/2011/12/organs-of-the-respiratory-system-larynx-bronchi-alveoli-diaphragm-trachea-pharynx-paranasal-sinuses.jpg [Accessed: 07 November, 2015]

[5] Gibson, D., & Macgregor, C. (2013). A Novel Solid State Non-Dispersive Infrared CO2 Gas Sensor Compatible with Wireless and Portable Deployment, *m*, 7079–7103. https://doi.org/10.3390/s130607079

[6] WHO.Int. (2016). *Chronic Respiratory Diseases*. Accessed: Jun. 13, 2016. [Online]. Available: http://www.who.int/respiratory/en/

[7] X. Wang and S. Wang, ``Hierarchical deployment optimization for wire-less sensor networks,'' *IEEE Trans. Mobile Comput.*, vol. 10, no. 7,pp. 1021_1041, Jul. 2011.

[8] Z. Cao, R. Zhu, and R.-Y. Que, ``A wireless portable system with microsensors for monitoring respiratory diseases,'' *IEEE Trans. Biomed. Eng.*,vol. 59, no. 11, pp. 3110_3116, Nov. 2012.

[9] Darling, R. B. (n.d.). EE-436 Medical Instrumentation Design of a Respiratory Capnometer, 1–13.

[10] Sakata, D. J., Matsubara, I., Gopalakrishnan, N. A., Westenskow, D. R., White, J. L., Yamamori, S., … Pace, N. L. (2009). FLOW-THROUGH VERSUS SIDESTREAM CAPNOMETRY FOR DETECTION OF END TIDAL

CARBON DIOXIDE IN THE SEDATED PATIENT, 115–122. https://doi.org/10.1007/s10877-009-9171-2

[11] M. Pekdemir, O. Cinar, S. Yilmaz, E. Yaka, M. Yuksel, Disparity between mainstream and sidestream end tidal carbon dioxide values and arterial carbon dioxide levels. Respir Care. respcare–02227 (2013)

[12] Yang, J., Chen, B., Burk, K., Wang, H., & Zhou, J. (2016). ORIGINAL RESEARCH A mainstream monitoring system for respiratory CO 2 concentration and gasflow. Journal of Clinical Monitoring and Computing, 30(4), 467–473. https://doi.org/10.1007/s10877-015-9739-yScholz, L., Perez, A. O., Knobelspies, S., Wöllenstein, J., & Palzer, S. (2015). MID-IR LED-based, Photoacoustic CO2 Sensor. *Procedia Engineering*, *120*, 1233–1236. https://doi.org/10.1016/j.proeng.2015.08.837

[13] Kasuya, Y., & Akc, O. (2018). Accuracy of Postoperative End-tidal P CO 2 Measurements with Mainstream and Sidestream Capnography in Non- obese Patients and in Obese Patients with and without Obstructive Sleep Apnea, (3), 609–615.

[14] Cinar O, Acar YA, Arziman I˙, Kilic E, Eyi YE, Ocal R. Can mainstream end-tidal carbon dioxide measurement accurately predict the arterial carbon dioxide level of patients with acute dyspnea in ed. AJEM. 2012;30(2):358–61.

[15] Westhorpe, R.N. and C. Ball, *The history of capnography.* Anaesth Intensive Care, 2010. **38**(4): p. 611.

[16] Jaffe, M.B., *Infrared Measurement of Carbon Dioxide in the Human Breath: "Breathe-Through" Devices from Tyndall to the Present Day.* Anesthesia & Analgesia, 2008. **107**(3): p. 890-904.

[17] Weaver, J., *The Latest ASA Mandate: CO(2) Monitoring For Moderate and Deep Sedation.* Anesthesia Progress, 2011. **58**(3): p. 111-112.

[18] D'Mello J, B.M., *Capnography.* Indian J Anaesth, 2002. **46**(4): p. 269-278.

[19] International Organization for Standardization. ISO 9918. Capnometers for Use with Humans- Requirements, 1993.

[20] American Association for Respiratory Care. Clinical Practice Guideline - Capnography / Capnometry during Mechanical Ventilation Respir Care. 40(12): 1321-4.

[21] Lee, B. R., Kester, W., & Seebeck, T. J. (2016). Complete Gas Sensor Circuit Using Nondispersive Infrared (NDIR), (October), 1–9.

[22] Manifold, C.A., et al., *Capnography for the Nonintubated Patient in the Emergency Setting.* The Journal of Emergency Medicine, 2013. **45**(4): p. 626-632.

[23] Loncar, M., Examiner, P., & Mitchell, T. (2006). (12) United States Patent, *2*(12).

[24] Cited, R., & Data, P. P. (2011). (12) United States Patent, *2*(12).

[25] Yang, J., & Wang, L. (2010). New mainstream double-end carbon dioxide capnograph for human respiration, 15(December), 1–6. https://doi.org/10.1117/1.3523620Mendes, L., et al., *NDIR Gas Sensor for Spatial Monitoring of Carbon Dioxide Concentrations in Naturally Ventilated Livestock Buildings.* Sensors, 2015. **15**(5): p. 11239.

[26] Carbonate Based CO_2 Sensors with High Performance, Th. Lang, H.-D. Wiemhöfer and W. Göpel, Conf.Proc.Eurosensors IX, Stockholm (S) (1995); Sensors and Actuators B, 34, 1996, 383–387.

[27] Reliable CO_2 Sensors Based with Silicon-based Polymers on Quartz Microbalance Transducers, R. Zhou, S. Vaihinger, K.E. Geckeler and W. Göpel, Conf.Proc.Eurosensors VII, Budapest (H) (1993); Sensors and Actuators B, 18–19, 1994, 415–420.

[28] Co2 Auto-Calibration Guide "Archived copy" *(PDF). Archived from* the original *(PDF)on 2014-08-19*. Retrieved 2014-08-19.*Arief-Ang, I.B.; Hamilton, M.; Salim, F. (2018-06*

[29] Yang, J., Wang, B., Xu, R., & Wang, L. (2010). A new real-time and precision capnography for human respiration carbon dioxide concentration, *25*(6), 399–408. https://doi.org/10.1177/0267659110380772

[30] Park IY, Park HJ, Lee JW, et al. A proposal of effective compensation method for IR lamp deterioration in NDIR type capnograph systems. IEICE Transactions on Fundamentals of Electronics Communications and Computer Sciences 2003; E86A(6): 1513–1516.

[31] Hodgkinson, J., Smith, R., On, W., Saffell, J. R., & Tatam, R. P. (2013). Non-dispersive infra-red (NDIR) measurement of carbon dioxide at 4 . 2μm in a c ompact and optically efficient sensor ., *186*(September), 580–588.

[32] J. Mayrwöger, P. Hauer, W. Reichl, R. Schwödiauer, C. Krutzler, B. Jakoby, Modeling of infrared gas sensors using a ray tracing approach, IEEE Sens. J. 10 (2010) 1691-1698.

[33] J. Mayrwöger, W. Reichl, P. Hauerc, C. Krutzler, B. Jakoby, CO2 monitoring using a simple Fabry–Perot-based germanium bolometer, Sensor. Actuat. B 154 (2011) 245–250.

[34] I. Sieber, H. Eggert, K.-H. Suphan, O. Nüssen, Optical modelling of the analytical chamber of an IR gas sensor, Proc. SPIE 4408 (2001) 272-282.

[35] Vincent, T. A., & Gardner, J. W. (2016). Sensors and Actuators B : Chemical A low cost MEMS based NDIR system for the monitoring of carbon dioxide in breath analysis at ppm levels. *Sensors & Actuators: B. Chemical*, *236*, 954–964. https://doi.org/10.1016/j.snb.2016.04.016

[36] Rodr, G. A. (2016). CO 2 measurement system based on pyroelectric detector, *62*(June), 278–281.

[37] Network, E., Technologies, N. S., Control, A. P., Sustainability, E., Cost, E., & Td, A. (2016). Control and Environmental Sustainability - EuNetAir 4 th International Workshop EuNetAir on Innovations and Challenges for Air Quality Control Sensors CMOS INFRARED EMITTERS AND DETECTORS FOR Environmental pollution is a BIG concern !

[38] Cell, G. (n.d.). Infrared Gas Sensors.

[39] Kwon J, Ahn G, Kim G, Kim JC, Kim H. A study on NDIR-based CO2 sensor to apply remote air quality monitoring system. ICCAS-SICE 2009

[40] Jiachen, Y., et al., A new real-time and precision capnography for human respiration carbon dioxide concentration. Perfusion, 2010. 25(6): p. 399-408.

[41] Yang, J., et al., A Low-Power and Portable Biomedical Device for Respiratory Monitoring with a Stable Power Source. Sensors, 2015. 15(8): p. 19618.

[42] Zhao, D., Miller, D., Xian, X., Tsow, F., & Forzani, E. S. (2014). A novel real-time carbon dioxide analyzer for health and environmental applications. Sensors and Actuators, B: Chemical, 195, 171–176. https://doi.org/10.1016/j.snb.2013.12.110

[43] Santoso D, Setiaji FD. Design and Implementation of Capnograph for Laparoscopic Surgery. International Journal of Information and Electronics Engineering 2013; 3: 523-528

[44] Bautista C, Patel B, Shah M, Connie L, Seifer B, Facas G. Portable capnography

[45] Scholz, L., Perez, A. O., Knobelspies, S., Wöllenstein, J., &Palzer, S. (2015). MID-IR LED-based, Photoacoustic CO2 Sensor. *Procedia Engineering*, *120*, 1233–1236. https://doi.org/10.1016/j.proeng.2015.08.837

[46] Zuleika, S., Kazemi, M., & Malarvili, M. B. (2014). Designing a Respiratory CO 2 Measurement Device for Home Monitoring of Asthma Severity, (December), 8–10.

[47] Sivaramakrishnan, S., Rajamani, R., & Johnson, B. D. (2010). Dynamic Model Inversion Techniques for Breath-by-Breath Measurement of Carbon Dioxide from Low Bandwidth Sensors, *10*(10), 1637–1646.

[48] CO 2 cuvettes and mainstream sensors Consumables and Accessories. (n.d.).

[49] Range, M., Dependence, T., & Dependence, P. (2018). Telaire T6615 | Dual Channel CO2 Sensor Module.

[50] Co, C. (n.d.). CO 2 nnect & Go, 2–3.

[51] Introduction, P., & Field, A. (n.d.). Product Introduction.

[52] Countries, O., Gmbh, L. C., S, L. C. S. A., Kingdom, U., & Countries, N. (n.d.). P RE L I M I NARY L11 / 21 Series Single Channel Current Mode Pyroelectric Detectors.

[53] Carbon dioxide images from PNNL, in microns. Available from: http://vpl.astro.washington.edu/spectra/co2pnnlimagesmicrons.htm. [accessed on 12 december 2018]

[54] Multisim software. Available from: https://en.wikipedia.org/wiki/NI_Multisim. [accessed on 10 december 2018]