

RATIOMETRIC METHOD FOR OZONE ABSORPTION CROSS SECTION  
MEASUREMENT

TAY CHING EN MARCUS

A thesis submitted in fulfilment of the  
requirements for the award for the degree of  
Doctor of Philosophy (Electrical Engineering)

Faculty of Electrical Engineering  
Universiti Teknologi Malaysia

JULY 2015

To my beloved family for unconditional support through ups and downs

## ACKNOWLEDGEMENTS

I would like to express my gratitude to Universiti Teknologi Malaysia (UTM) and Ministry of Higher Education (MOHE) Malaysia for supporting this research work under Research University Grant (RUG) Scheme grant no: 05J60 and grant no: 04H35, Fundamental Research Grant Scheme (FRGS) grant no: 4F317, and UTM Zamalah Fellowship. In addition, I thank my main supervisor, Assoc. Prof. Dr. Mohd Haniff bin Ibrahim for constructive feedback on my writings, academic advice and financial support to purchase equipments for experiment. I am grateful to my cosupervisor, Dr. Nor Hafizah binti Ngajikin for commenting my writings and financial support to purchase equipments for experiment. I thank Dr. Asrul Izam bin Azmi for his time and effort spent to review my writings. I show appreciation to Assoc. Prof. Dr. Sevia Mahdaliza bin Idrus for financial support to purchase equipments for experiment. I appreciate colleagues Michael David, Maslina Yaacob, Mohd Rashidi Salim and Nabihah Hussin for constructive criticisms. In short, I extend my appreciation to people that have helped to me at various occasions to ensure successful outcome of this study.

## ABSTRACT

Ultraviolet absorption spectroscopy has been practised for ozone concentration measurement because the method of measurement is fast and reliable. Ratiometric method corrects intensity drift of light source for improvement of measurement stability. However, ozone absorption cross section may not be determined via ratiometric method because of limitation of existing Beer–Lambert law. Absorption cross section defines strength of absorption, which is an important parameter for calculation of ozone concentration. Firstly, optical path length of gas cell that suits dynamic range of ozone monitor in this work (less than 1000 ppm) is determined. Based on spectralcalc.com simulation, gas cells of optical path lengths of 5 cm, 10 cm and 20 cm are optimized for concentration measurement from 494.1 ppm to 988.1 ppm, 247.0 ppm to 494.1 ppm and 123.5 ppm to 247.0 ppm respectively. Secondly, Beer–Lambert law deviation is observed when long gas cell of optical path length 10 cm is used to measure high ozone concentration from 357 ppm to 971 ppm. Typically, ozone is sampled using strong absorption wavelength for high sensitivity measurement. When strong absorption wavelengths cause saturation, linearity of measurement is preserved by sampling ozone using weak absorption wavelength 279.95 nm. Thirdly, temperature and pressure stability of ozone absorption cross section are verified using spectralcalc.com simulation. Finally, a novel equation is established based on Beer–Lambert law for measurement of ozone absorption cross section via ratiometric method. The equation is verified for ozone concentration measurement from 450 ppm to 989 ppm using short gas cell of optical path length 5 cm, sampling wavelength 260.99 nm and reference wavelength 377.05 nm. The equation is attractive to researchers in areas of absorption spectroscopy and optical gas sensor because ratiometric method is gaining popularity for high stability ozone concentration measurement.

## ABSTRAK

Spektroskopi penyerapan ultraungu sering diguna untuk mengukur kepekatan ozon kerana cara pengukuran ini cepat dan boleh dipercayai. Kaedah metrik nisbah meningkatkan kestabilan pengukuran kerana keamatan cahaya yang kurang stabil dipertimbangkan. Keratan rentas penyerapan ozon tidak dapat dikira melalui kaedah metrik nisbah kerana kekurangan hukum Beer–Lambert yang sedia ada. Keratan rentas penyerapan ozon adalah parameter penting untuk pengiraan kepekatan ozon. Pertama, panjang sel gas yang bakal mengukur julat kepekatan ozon yang boleh diukur oleh alat pengukur ozon (kurang dari 1000 ppm) dikenal pasti. Hasil simulasi *spectralcalc.com* menunjukkan kepekatan ozon yang bakal diukur oleh sel gas 5 cm, 10 cm dan 20 cm, adalah 494.1 ppm ke 988.1 ppm, 247.0 ppm ke 494.1 ppm dan 123.5 ppm ke 247.0 ppm. Kedua, pelencongan hukum Beer–Lambert diperhatikan apabila sel gas 10 cm digunakan untuk pengukuran kepekatan ozon dari 357 ppm ke 971 ppm. Biasanya, panjang gelombang yang kuat diserap oleh ozon digunakan untuk pengukuran yang peka. Apabila panjang gelombang yang kuat diserap oleh ozon menyebabkan ketepuan, hubungan linear pengukuran dikekalkan dengan menggunakan panjang gelombang yang lemah diserap oleh ozon 279.95 nm. Ketiga, kestabilan keratan rentas penyerapan ozon pada suhu dan tekanan berlainan disahkan melalui simulasi *spectralcalc.com*. Akhirnya, persamaan baru diperolehi dari hukum Beer–Lambert untuk mengira keratan rentas penyerapan ozon melalui kaedah metrik nisbah. Persamaan tersebut disahkan melalui pengukuran kepekatan ozon dari 450 ppm ke 989 ppm menggunakan sel gas 5 cm, panjang gelombang sampel 260.99 nm dan panjang gelombang rujukan 377.05 nm. Persamaan tersebut menyumbang kepada bidang spektroskopi penyerapan dan pengukuran gas melalui kaedah optik kerana kaedah metrik nisbah semakin kerap digunakan untuk pengukuran kepekatan ozon yang stabil.

## TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	<b>DECLARATION</b>	ii
	<b>DEDICATION</b>	iii
	<b>ACKNOWLEDGEMENTS</b>	iv
	<b>ABSTRACT</b>	v
	<b>ABSTRAK</b>	vi
	<b>TABLE OF CONTENTS</b>	vii
	<b>LIST OF TABLES</b>	xi
	<b>LIST OF FIGURES</b>	xiii
	<b>LIST OF ABBREVIATIONS</b>	xvii
	<b>LIST OF SYMBOLS</b>	xviii
	<b>LIST OF APPENDICES</b>	xx
<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
	1.1 Introduction to Ozone and Its Applications	1
	1.2 Review of Ozone Sensors	4
	1.3 Problem Formulation	7
	1.4 Motivation of Research	8
	1.5 Objectives of Research	9
	1.6 Scope of Research	10
	1.7 Overview of Thesis	11
<b>2</b>	<b>THEORETICAL BACKGROUND FOR ABSORPTION BASED OZONE SENSOR</b>	<b>14</b>
	2.1 Introduction	14

2.2	Derivation of Beer–Lambert Law for Concentration Measurement	14
2.3	Beer–Lambert Law for Ratiometric Method Calculation	19
2.4	Twyman–Lothian Perspective for Disobedience of Beer–Lambert Law at High and Low Transmittance	20
2.5	Limitations of Beer–Lambert Law	21
2.6	Prerequisites of Beer–Lambert Law	23
2.7	Review of Ozone Absorption Cross Section	24
2.8	Review of Sensor Performance Specifications	30
2.9	Sensitivity for Selection of Maximum Absorption Wavelength	35
2.10	Summary	36
<b>3</b>	<b>INSTRUMENTATION FOR ABSORPTION BASED OZONE SENSOR</b>	<b>37</b>
3.1	Introduction	37
3.2	Review of Sensor Instruments	37
3.2.1	Optical Components	37
3.2.2	Gas Components	44
3.2.3	Gas Cell Construction for Ozone Application	50
3.2.4	Gas Cell Diameter and Sensor Sensitivity	53
3.3	Gas Cell Fabrication Decision	54
3.4	Summary	56
<b>4</b>	<b>OPTICAL PATH LENGTH OPTIMIZATION FOR HIGH OZONE CONCENTRATION MEASUREMENT</b>	<b>58</b>
4.1	Introduction	58
4.2	Concentration Measurement Range Optimization for Specific Optical Path Length	59
4.2.1	Simulation Methodology	59
4.2.2	Simulation Result of Maximum and Minimum Absorption Wavelength	61

4.2.3	Simulation Result of Maximum Absorption Cross Section	64
4.2.4	Simulation Result of Concentration Measurement Range at Specific Optical Path Length	67
4.3	Limitation of Long Gas Cell for High Ozone Concentration Measurement	68
4.3.1	Simulation of Absorption Cross Section Spectrum	69
4.3.2	Experimental Methodology using Long Gas Cell	70
4.3.3	Experimental Result of Sensor Linearity and Recommendations	72
4.4	Summary	76
<b>5</b>	<b>CHARACTERIZATION OF OZONE ABSORPTION CROSS SECTION</b>	<b>77</b>
5.1	Introduction	77
5.2	Simulation of Temperature Dependence of Absorption Cross Section	78
5.2.1	Simulation Result of Temperature Dependence	78
5.3	Simulation of Pressure Dependence of Absorption Cross Section	81
5.3.1	Simulation Result of Pressure Dependence	82
5.4	Ratiometric Method for Maximum Absorption Cross Section Determination	84
5.4.1	Experimental Methodology using Short Gas Cell	85
5.4.2	Experimental Result of Maximum and Minimum Absorption Wavelength	87
5.4.3	Experimental Result of Real Time Ozone Concentration Measurement	89
5.4.4	Experimental Result of Maximum Absorption Cross Section	91
5.5	Summary	94



<b>6</b>	<b>CONCLUSIONS, CONTRIBUTIONS AND FUTURE WORK</b>	<b>95</b>
6.1	Conclusions	95
6.2	Contributions	96
6.3	Recommendations for Future Work	98
	<b>REFERENCES</b>	<b>100</b>
	Appendices A–C	116–134

**LIST OF TABLES**

<b>TABLE NO.</b>	<b>TITLE</b>	<b>PAGE</b>
1.1	Physical Characteristics of Ozone Gas	2
2.1	Comparison of Ozone Absorption Cross Section among Hartley, Huggins, Huggins Chappuis Minimum and Chappuis Band	26
2.2	Performance Specifications of Absorption Based Ozone Sensor in Previous Work	31
3.1	Comparison of Optical Components between This Work and Previous Work	38
3.2	Comparison of Gas Components between This Work and Previous Work	44
3.3	Comparison of Ozone Gas Cell Construction between This Work and Previous Work	50
3.4	Details of Gas Cell Fabrication	55
3.5	Selection of Experimental Instruments for This Work	57
4.1	Comparison of Sampling and Reference Wavelengths among This Simulation and Previous Experiments	64
4.2	Comparison of Maximum Absorption Cross Section among This Simulation and Previous Experiments	66
4.3	Comparison of Dynamic Range among This Simulation and Previous Experiments for Ozone Concentration Measurement via Ultraviolet Absorption Spectroscopy	67

4.4	Comparison of Linearity among Selected Sampling Wavelengths	74
4.5	Comparison of Absorption Cross Section between This Experiment and Simulation	75
5.1	Temperature Dependence Comparison among Maximum Absorption Cross Section in This Simulation and Previous Experiments	81
5.2	Comparison of Ozone Absorption Cross Section among This Experiment and Previous Experiments	93
A.1	Comparison of Ozone Sensing Techniques	117

## LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
1.1	Scope of research of this study	11
2.1	Graph of absorbance versus transmittance based on theoretical calculation from Equation 2.6	16
2.2	Model to illustrate exponential reduction of light intensity after passing through ozone of equal concentration in a fixed volume cylindrical gas cell	17
2.3	Twyman–Lothian curve based on transmittance error 0.10 % (Hughes, 1963)	21
2.4	Ozone absorption cross section spectrum simulated based on spectralcalc.com gas cell simulator at temperature 300 K, pressure 1 atm, ozone concentration 500 ppm and optical path length 5 cm	25
3.1	Ocean Optics DH-2000 deuterium tungsten halogen light source in operation. The instrument is connected to an optical fibre.	41
3.2	Ocean Optics QP400-025-SR premium solarisation resistant fibre of 25 cm length and 400 $\mu\text{m}$ diameter with protection cap on for storage	42
3.3	Ocean Optics HR4000CG-UV-NIR high resolution spectrometer in operation. The instrument is connected to an optical fibre and USB connection to computer.	43
3.4	Ocean Optics 74-UV collimating lens ready for connection to optical fibre and gas cell	44
3.5	Longevity Resources corona discharge ozone generator EXT50. Input to the generator is pure oxygen supply via vinyl tube. Output from the generator is ozone via silicone tube.	47
3.6	Purified oxygen supply at 99.999 % purity. The oxygen	

	supply is connected to pressure regulator to control speed of oxygen flow to ozone generator. Vinyl tube is used for oxygen transportation.	48
3.7	2B Technologies ozone monitor model 106-M is warming up for experiment	49
3.8	Brass male pneumatic fitting for silicone tube of 4 mm internal diameter and 6 mm external diameter	53
3.9	A set of 3/8 UNF X 24 Majesta hand tap for threading of aluminium gas cell to fit SMA 905 connector of Ocean Optics 74-UV collimating lens	56
3.10	From left to right, prefabricated aluminium rod of 0.64 cm internal diameter, fabricated aluminium gas cells of length 6.3 cm, 11.3 cm and 21.3 cm. The gas cell is fitted with brass pneumatic fittings for gas inlet and outlet. Both sides of gas cell will be fitted to Ocean Optics 74-UV collimating lens for light input and output. Connections are tighten with PTFE tape to prevent gas leakage.	56
4.1	Graphic user interface of spectralcalc.com gas cell simulator for wavelength selection	60
4.2	Graphic user interface of spectralcalc.com gas cell simulator for selection of gas, isotope, volume mixing ratio (VMR), optical path length, pressure, temperature and line list database	60
4.3	Transmittance spectrum of ozone obtained via spectralcalc.com gas cell simulator at wavelength from 240 nm to 270 nm, optical path length 5 cm, temperature 300 K, pressure 1013.25 mbar and ozone concentration from 35.64 ppm to 2102.70 ppm	62
4.4	Transmittance spectrum of ozone obtained via spectralcalc.com gas cell simulator at wavelength from 360 nm to 400 nm, optical path length 20 cm, temperature 300 K, pressure 1013.25 mbar and ozone concentration 247.0 ppm	63
4.5	Graph of concentration versus natural logarithm of transmittance obtained from this simulation at maximum absorption wavelength 255.442 nm, temperature 300 K, pressure 1 atm and optical path length 5 cm, 10 cm and 20 cm	65
4.6	Graphic user interface of spectralcalc.com line list browser for selection of gas, wavenumber, pressure, temperature and line list database	69

4.7	Ozone absorption cross section spectrum simulated via spectralcalc.com line list browser at temperature 300 K and pressure 0 torr	70
4.8	Experimental setup for ozone concentration measurement via ultraviolet absorption spectroscopy using long gas cell of 10 cm optical path length	71
4.9	Transmissive aluminium gas cell of 0.64 cm internal diameter and 10 cm optical path length. The gas cell is fitted with brass pneumatic fittings for gas inlet and outlet. The gas cell is fitted to Ocean Optics 74-UV collimating lens for light input and output. Connections are tightened with PTFE tape to prevent gas leakage.	72
4.10	Graph of natural logarithm of transmittance (sensor output) versus actual ozone concentration (commercial ozone monitor output) based on experimental result at optical path length 10 cm and selected sampling wavelengths	73
5.1	Graph of absorption cross section versus wavelength at temperature from 200 K to 300 K and pressure 0 torr obtained from simulation via spectralcalc.com line list browser	79
5.2	Graph of maximum absorption cross section versus temperature at pressure 0 torr obtained from simulation via spectralcalc.com line list browser	80
5.3	Ozone absorption cross section spectrum simulated based on spectralcalc.com gas cell simulator at optical path length 0.20 m, temperature 300 K, pressure from 0.1 atm to 3 atm and concentration 123.5 ppm	83
5.4	Graph of maximum absorption cross section versus pressure simulated using spectralcalc.com gas cell simulator at maximum absorption wavelength 255.442 nm, optical path length 0.20 m, temperature 300 K, and concentration 123.5 ppm	83
5.5	Transmissive aluminium gas cell of 0.64 cm internal diameter and 5 cm optical path length	86
5.6	Experimental block diagram for ozone concentration measurement using ultraviolet absorption spectroscopy and short gas cell of 5 cm optical path length	87
5.7	Transmittance spectrum of ozone obtained through experiment at wavelength from 210.03 nm to 409.95 nm, optical path length 5 cm and ozone concentration from 452 ppm to 976 ppm	88

5.8	Graph of actual ozone concentration (commercial ozone monitor output) and sensor output versus time obtained through experiment using maximum absorption wavelength 260.99 nm, minimum absorption wavelength 377.05 nm and optical path length 5 cm	89
5.9	Graph of minimum absorption wavelength intensity (sensor output) versus time obtained through experiment at optical path length 5 cm and concentration from 450 ppm to 989 ppm	91
5.10	Graph of sensor output versus actual ozone concentration (commercial ozone monitor output) obtained through experiment using maximum absorption wavelength 260.99 nm, minimum absorption wavelength 377.05 nm and optical path length 5 cm	92

**LIST OF ABBREVIATIONS**

BIPM	-	<i>Bureau International des Poids et Mesures</i> or International Bureau of Weights and Measures
DH	-	Deuterium halogen
DUV	-	Deep ultraviolet
FDA	-	Food and Drug Administration
FWHM	-	Full width half maximum
HITRAN	-	High resolution transmission
HR	-	High resolution
LED	-	Light emitting diode
LPM	-	Litres per minute
NASA	-	National Aeronautics and Space Administration
OSHA	-	Occupational Safety and Health Administration
PMMA	-	Polymethyl methacrylate
ppb	-	Parts per billion
ppm	-	Parts per million
ppt	-	Parts per trillion
PTFE	-	Polytetrafluoroethylene
USD	-	United States Dollar
UV	-	Ultraviolet
Vis	-	Visible
VMR	-	Volume mixing ratio



## LIST OF SYMBOLS

$A$	-	Absorbance of light (no unit)
$A_g$	-	Cross sectional area of gas cell in $m^2$
$c_2$	-	Concentration of ozone in second system that varies in temperature, pressure or volume from first system
$c_s(\text{ppm})$	-	Standard gas concentration given by commercial gas monitor in ppm by volume
$c_{(\text{g m}^{-3})}$	-	Density of ozone in $\text{g m}^{-3}$
$c_{(\text{g Nm}^{-3})}$	-	Density of ozone at pressure 1 atm and temperature 273.15 K in $\text{g Nm}^{-3}$
$c_{(\text{mol m}^{-3})}$	-	Concentration of ozone in $\text{mol m}^{-3}$
$c_{(\text{ppm})}$	-	Concentration of ozone in ppm by volume
$c_{(\text{wt}\%)}$	-	Concentration of ozone in percentage by weight
$I$	-	Light intensity in count
$I_0$	-	Output intensity of absorbing wavelength passing ozone at zero concentration in count
$I_{0r}$	-	Output intensity of non absorbing wavelength passing ozone at non zero concentration in count
$I_t$	-	Output intensity of absorbing wavelength passing ozone at non zero concentration in count
$I_s$	-	Forward scattering contribution of absorbing wavelength in count
$k$	-	Absorption coefficient of ozone in $\text{m}^{-1}$
$k_1$	-	Constant used to relate $I_0$ and $I_{0r}$ in ratiometric calculation
$k_B$	-	Boltzmann's constant, $1.362595903 \times 10^{-28} \text{ atm m}^3 \text{ K}^{-1} \text{ molecule}^{-1}$
$L$	-	Length of sample in m
$l_s$	-	Optical path length in m
$N$	-	Number density in $\text{molecule m}^{-3}$
$N_A$	-	Avogadro's constant, $6.02214199 \times 10^{23} \text{ molecule mol}^{-1}$

$n_{(\text{cm}^{-1})}$	-	Wavenumber in $\text{cm}^{-1}$
$n_f$	-	Mole fraction of ozone (no unit)
$n_m$	-	Amount of ozone gas in mol
$n_T$	-	Total amount of gas in mol
$P$	-	Total pressure of gas in atm
$p$	-	Partial pressure of ozone in atm
$r$	-	Norm of residual
$R$	-	Ideal gas constant, $8.205746 \times 10^{-5} \text{ atm m}^3 \text{ mol}^{-1} \text{ K}^{-1}$
$S$	-	Forward scattering correction factor (no unit)
$t$	-	Time in s
$T$	-	Absolute temperature in K
$T_r$	-	Transmittance of light (no unit)
$T_{rr}$	-	Constant used to relate $I_t$ and $I_{0r}$ in radiometric calculation
$V$	-	Total volume of gas in $\text{m}^3$
$v$	-	Volume of ozone in $\text{m}^3$
$V_m$	-	Molar volume of ozone in $\text{m}^3 \text{ mol}^{-1}$
$y_i$	-	A data point in a graph
$y_{i\text{best}}$	-	A data point at best fit line
$\Delta c$	-	Error of ozone concentration
$\Delta c/c$	-	Relative error of ozone concentration
$\Delta T_r$	-	Absolute error of transmittance
$\epsilon$	-	Molar absorption coefficient in $\text{m}^2 \text{ mol}^{-1}$
$\epsilon_{10}$	-	Decadic molar absorption coefficient in $\text{m}^2 \text{ mol}^{-1}$
$\lambda$	-	Wavelength in nm
$\rho$	-	Ozone density at 1000000 ppm in $\text{g m}^{-3}$
$\sigma$	-	Absorption cross section of ozone in $\text{m}^2 \text{ molecule}^{-1}$
$\sigma_{\text{experiment}}$	-	Absorption cross section in this experiment
$\sigma_{\text{simulation}}$	-	Absorption cross section in this simulation via spectralcalc.com line list browser
$\sigma_{\text{this}}$	-	Absorption cross section in this work
$\sigma_{\text{previous}}$	-	Absorption cross section in previous work
$\sigma_{200\text{K}}$	-	Absorption cross section at temperature 200K
$\sigma_{300\text{K}}$	-	Absorption cross section at temperature 300K
$\omega$	-	Molar mass of ozone, $48 \text{ g mol}^{-1}$

**LIST OF APPENDICES**

<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	Summary of Ozone Sensing Techniques	117
B	Conversion Fundamentals, Relationships and Variations in Beer–Lambert Law	125
C	List of Publications	131

## CHAPTER 1

### INTRODUCTION

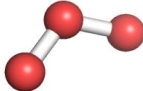
#### 1.1 Introduction to Ozone and Its Applications

Ozone (triatomic oxygen, O<sub>3</sub>) is described to be good up high, but bad nearby (United States Environment Protection Agency, 2003). Ozone at stratosphere protects the earth from harmful ultraviolet sun rays. On ground level, ozone pollutes the air. Ozone is generated from anthropogenic emissions such as organic volatile compound and oxides of nitrogen in presence of sunlight (Arif and Abdullah, 2011; Cooper *et al.*, 2010; Weschler, 2000; Yadav *et al.*, 2014). At industrial and urban areas in Peninsular Malaysia, high concentration of ground level ozone is recorded from April to June because of dry weather (Rajab *et al.*, 2011). In wet weather, rain cleanses nitrogen oxides in the air, which hinders formation of ozone (Rajab *et al.*, 2010). Ozone has distinctive pungent smell. However, inhalation of ozone causes pulmonary disease (Jakpor, 2009). Based on OSHA standard, a worker should not expose to ozone more than 0.1 ppm in 8 hours (United States Department of Health and Human Services and United States Department of Labour, 1978). Based on Malaysian industry code of practice on indoor air quality, acceptable ozone exposure limit is 0.05 ppm in 8 hours (Department of Occupational Safety and Health, 2010). Nonetheless, ozone is generated purposely for benefit of humankind. Safe application of ozone in enclosed environment is strongly recommended.

Table 1.1 summarizes physical characteristics of ozone gas. Firstly, ozone has strong oxidizing property. This feature is often applied in disinfection technology. Secondly, the gas is invincible at low concentration, but is pale blue at high

concentration. The pale colour is a useful feature to measure ozone concentration using visible wavelength (O’Keeffe *et al.*, 2007; O’Keeffe *et al.*, 2005a; O’Keeffe *et al.*, 2005b; O’Keeffe *et al.*, 2005c; Teranishi *et al.*, 2013). Thirdly, ozone is unstable in nature, as it will revert to oxygen. In a sealed container, ozone half life ranges from 39 minutes to 25.4 hours, which is dependent on air flow rate, temperature and humidity (McClurkin *et al.*, 2013). In ventilated indoor environment, ozone half life ranges between 7 minutes and 10 minutes, which is mainly dependent on outdoor air exchange and surface removal (Weschler, 2000). Ozone lifespan is long when air is still, cold and dry (McClurkin *et al.*, 2013). Moving ozone molecules interact among themselves to dissociate to oxygen (McClurkin *et al.*, 2013). The higher the temperature, the faster the ozone dissociation to oxygen (Yagi and Tanaka, 1978). Ozone reacts with water to form hydroxyl radical, which accelerates ozone destruction (Campbell, 1986; Chen *et al.*, 2011; Mikoviny *et al.*, 2007; Pekárek, 2008; Skalný *et al.*, 2008). Ozone lifespan is greatly reduced when it is in contact with large surface area such as carpet and fleece (Weschler, 2000). Since ozone has limited lifespan, ozone cannot be transported and should be generated on site.

**Table 1.1:** Physical Characteristics of Ozone Gas

Details	Description
Name	Ozone (triatomic oxygen)
Atomic view (Tejerina, 2009)	
Chemical symbol	O <sub>3</sub>
Description	Toxic and strongly oxidizing
Colour	Colourless at low concentration. Pale blue at high concentration.
Smell	Pungent
Stability	Unstable. Quick breakdown to oxygen.
Molecular weight, $\omega$	48 g mol <sup>-1</sup> (Department of Occupational Safety and Health, 2010)
Density, $P\omega/(RT)$ (derivation in Appendix B)	2141 g m <sup>-3</sup> at pressure 1 atm and temperature 273.15 K. 1962 g m <sup>-3</sup> at pressure 1 atm and temperature 298.15 K.
Boiling temperature	-112 °C at pressure 1 atm (Department of Occupational

	Safety and Health, 2010)
Explosive risk	Concentration exceeds 10 % by volume (Koike <i>et al.</i> , 1999)

Ozone, ultraviolet and chlorine disinfection technologies have begun since early 20th century (Sonntag and Gunten, 2012). Usually, ozone and ultraviolet light are used simultaneously to treat wastewater (Rivas *et al.*, 2009) and pack food (Naitou and Takahara, 2008). Ozone kills 99 % surface virus at 47 to 223 min mg m<sup>-3</sup> doses (Tseng and Li, 2008). Ozone dose is product of ozone concentration and contact time (Tseng and Li, 2008). Similarly, UV-C rays damage genes of micro-organisms. For example, either 0.38 mg dm<sup>-3</sup> ozone concentration, or 270 J dm<sup>-3</sup> ultraviolet dose at wavelength 254 nm disinfects seawater completely (Penru *et al.*, 2013). Unlike light travelling in straight line, ozone sanitizes hard to reach areas such as food. Exposure of 0.7 µL L<sup>-1</sup> of gaseous ozone for 3 minutes preserves red bell peppers better than liquid chlorine (Horvitz and Cantalejo, 2012). This is because chlorine leaves behind toxic residues such as trihalomethanes (Gottschalk *et al.*, 2010). In short, ozone is an environmentally friendly alternative for disinfection purpose.

Ozone has been approved by Food and Drug Administration (FDA) for food contact since 2001 (Lake, 2001). Today ozone is applied to reduce bacteria, pesticide residue and microbial spoilage for long term storage of fruits and vegetables (Tiwari and Muthukumarappan, 2012). This is effective if ozone is applied at high relative humidity environment above 80 % (Tiwari and Muthukumarappan, 2012). However, appropriate gaseous ozone concentration is required for this application. This is because extreme concentration of ozone degrades sensory quality of fruits, especially aroma (Tiwari and Muthukumarappan, 2012). Exposure of tomatoes to 0.025 g m<sup>-3</sup> gaseous ozone for 2 hours daily for 16 days extends lifetime of tomatoes (3 of 22 damaged) compared to tomatoes without treatment (12 of 22 damaged) or treatment at 0.045 g m<sup>-3</sup> (6 of 22 damaged) (Venta *et al.*, 2010). Likewise, 0.3 ppm ozone exposure for 420 minutes reduces *Bacillus cereus* count in processed rice by 1.63 log (Shah *et al.*, 2011). Exposure of 8 ± 0.2 ml s<sup>-1</sup> ozone flow rate below 20 minutes enriches antioxidant contents (phenol and flavonoid) of honey pineapple and banana (*pisang mas*) (Alothman *et al.*, 2010). However, vitamin C content diminishes. Pyrimethanil is

a fungicide used in vineyard (Gabriolotto *et al.*, 2009). To remove pyrimethanil from grapes, exposure of grapes to  $0.3 \mu\text{L L}^{-1}$  ozone concentration for 36 days (51.6 % removal) is more effective than air (14.5 % removal) (Karaca *et al.*, 2012). Similar trend is observed in aqueous ozone treatment. For example, 0.075 ppm and 0.15 ppm aqueous ozone concentrations preserve strawberry for 3 weeks, but 0.25 ppm aqueous ozone concentration deteriorates strawberry (Aday *et al.*, 2014). Not much differences are observed for ozone exposure times between 2 minutes and 5 minutes (Aday *et al.*, 2014). In short, ozone sanitizes, preserves, improves nutrition and reduces fungicide of fruits and vegetables at appropriate concentration.

## 1.2 Review of Ozone Sensors

Ozone has played an important role for disinfection applications; thus, ozone sensor is required to monitor ozone concentration. Ozone has been measured from different perspectives. All sensors have their own advantages and drawbacks; therefore, selecting suitable type of sensor for specific application is important. Examples of sensing method include the optical absorption spectroscopy (Aoyagi *et al.*, 2012; Degner *et al.*, 2009; Degner *et al.*, 2010; O’Keeffe *et al.*, 2005a; O’Keeffe *et al.*, 2005b; O’Keeffe *et al.*, 2005c; O’Keeffe *et al.*, 2007; O’Keeffe *et al.*, 2008; Maria and Bartalesi, 2012; Maria and Rizzi, 2009; Maria *et al.*, 2008; Teranishi *et al.*, 2013), cavity ringdown laser absorption spectroscopy (Washenfelder *et al.*, 2011), Fabry–Perot interferometry (Puschell *et al.*, 2005), interferometric photoacoustic spectroscopy (Köhring *et al.*, 2012), metal oxide semiconductor (Aguir *et al.*, 2002; Arshak *et al.*, 2007; Carotta *et al.*, 2011; Chien *et al.*, 2010; Ghaddab *et al.*, 2012; Martins *et al.*, 2004; Wagner *et al.*, 2011; Wang *et al.*, 2011), carbon (Park *et al.*, 2009; Sano and Ohtsuki, 2007), dye (Maruo, 2007; Maruo *et al.*, 2009; Maruo *et al.*, 2010; Miwa *et al.*, 2009), decomposition heat (Nakagawa *et al.*, 2001) and soft sensor (Zhang *et al.*, 2010). Summary to compare the measurement techniques is attached in Appendix A.

Optical absorption spectroscopy works based on the principle that every gas absorbs light at specific wavelength. In this study, optical absorption spectroscopy is

selected to measure ozone concentration. Advantages of optical absorption spectroscopy over other measurement techniques for ozone concentration measurement are discussed as follow:

Firstly, strength of absorption based sensor is short response time. For example, response time between 0.7 s and 60 s is typically reported in absorption spectroscopy (Aoyagi *et al.*, 2012; Degner *et al.*, 2009; Degner *et al.*, 2010; Maria and Bartalesi, 2012; Maria and Rizzi, 2009; Maria *et al.*, 2008; O’Keeffe *et al.*, 2005a; O’Keeffe *et al.*, 2007; Teranishi *et al.*, 2013). Similarly, soft sensor has fast response time (0.58 s) (Zhang *et al.*, 2010). Other sensors typically require longer time for ozone measurement. For example, carbon nanohorn sensor requires response time of 1400 s (Sano and Ohtsuki, 2007). Reported response times for metal oxide semiconductor sensors are 45 s (Chien *et al.*, 2010), 240 s (Arshak *et al.*, 2007), few minutes (Carotta *et al.*, 2011) and 40 minutes (Ghaddab *et al.*, 2012). Early work of dye sensor in glass substrate requires a week to respond to presence of ozone (Maruo, 2007). After that, response time of dye sensor in paper substrate is improved to few hours (Maruo *et al.*, 2009; Maruo *et al.*, 2010; Miwa *et al.*, 2009). Thus, absorption based sensor is suitable for real time measurement.

Secondly, absorption based sensor is reliable for long lasting operation. This is because light interacts with ozone without physical contact. Metal oxide semiconductor sensor requires oxidation of sensing material by ozone (Chien *et al.*, 2010). Dye sensor is disposable, as measurement is irreversible (Maruo, 2007; Maruo *et al.*, 2009; Maruo *et al.*, 2010; Miwa *et al.*, 2009). Absorption based sensor can be used repeatedly. Deuterium lamp operates up to 1000 hours (Ocean Optics, 2009); whereas, LED operates beyond 10000 hours (Aoyagi *et al.*, 2012). Absorption based sensor is often designed for operation in harsh environment (Degner *et al.*, 2009; Degner *et al.*, 2010; O’Keeffe *et al.*, 2005a; O’Keeffe *et al.*, 2005b; O’Keeffe *et al.*, 2005c; O’Keeffe *et al.*, 2007; Maria and Bartalesi, 2012; Maria and Rizzi, 2009; Maria *et al.*, 2008). Thus, absorption based sensor is robust because it can be used repeatedly at minimal maintenance.



Thirdly, absorption based sensor is capable to measure moderate to high ozone concentration. For example, concentration measurement from  $25 \text{ g m}^{-3}$  to  $126 \text{ g m}^{-3}$  (12821.48 ppm to 64620.25 ppm at temperature 300 K and pressure 1 atm) has been reported in visible absorption spectroscopy (O’Keeffe *et al.*, 2005a; O’Keeffe *et al.*, 2007). Not many sensors are able to measure such high concentrations. The closest sensor for comparison is decomposition heat sensor, which measures  $0 \text{ g m}^{-3}$  to  $100 \text{ g m}^{-3}$  (0 ppm to 51285.91 ppm at temperature 300 K and pressure 1 atm) (Nakagawa *et al.*, 2001). Other sensors are designed for moderate to low concentration measurement. For example, concentration measurement from  $0.03 \text{ g m}^{-3}$  to  $0.97 \text{ g m}^{-3}$  (15.39 to 497.47 ppm at temperature 300 K and pressure 1 atm) has been reported in ultraviolet absorption spectroscopy (O’Keeffe *et al.*, 2005c; O’Keeffe *et al.*, 2007). This dynamic range is higher than metal oxide semiconductor sensors, which dynamic ranges are reported to be from 0 to 500 ppb (Arshak *et al.*, 2007), 20 ppb to 2.4 ppm (Wagner *et al.*, 2011) and 10 ppb to 200 ppm (Wang *et al.*, 2011). Small ozone concentration measurement from 26 ppt to 250 ppb is reported in cavity ringdown laser absorption spectroscopy (Washenfelder *et al.*, 2011).

Fourthly, absorption based sensor is immune to electromagnetic interference. This is an important safety feature for ozone monitoring in high voltage environment (Maria and Bartalesi, 2012; Maria and Rizzi, 2009; Maria *et al.*, 2008). Light is transferred through fibre optics, which does not impose fire hazard. Risk of fire is reduced when absorption based ozone sensor is used to detect spark in switchboard (Maria and Bartalesi, 2012; Maria and Rizzi, 2009; Maria *et al.*, 2008). Metal oxide semiconductor sensors rely on conductivity (Aguir *et al.*, 2002; Carotta *et al.*, 2011; Martins *et al.*, 2004), resistivity (Chien *et al.*, 2010) or resistance (Arshak *et al.*, 2007; Ghaddab *et al.*, 2012; Wang *et al.*, 2011; Wagner *et al.*, 2011) for ozone concentration measurement. Similarly, carbon sensors rely on resistance (Park *et al.*, 2009; Sano and Ohtsuki, 2007) to measure ozone concentration. Interference of electrical signal may avoided if absorption based sensor is used.

Fifthly, absorption based sensor operates without the need of additional heating. Heating of sensor requires additional cost and energy. For example, sensor that measure decomposition heat of ozone works at high temperature 680 K (Nakagawa *et*

*al.*, 2001). Early work of metal oxide semiconductor ozone sensor requires high working temperature from 470 K to 720 K (Aguir *et al.*, 2002). Similarly, carbon nanotube sensors require annealing in furnace at 300 °C (Ghaddab *et al.*, 2012) or 350 °C (Park *et al.*, 2009). Thus, absorption based sensor is favourable for ozone concentration measurement because it can be operated at ambient temperature.

Disadvantage of absorption based ozone sensor is requirement of large amount of start up capital for purchase of optical instruments. Optical components that work in ultraviolet region are more expensive than visible region. For example, polymethyl methacrylate (PMMA) plastic optical fibre for visible light transmission is more cost effective than solarization resistant fibre for ultraviolet light transmission (O’Keeffe *et al.*, 2007). The benefit of choosing ultraviolet wavelength over visible wavelength for ozone concentration measurement is the ability to differentiate small amount of concentration. Resolution of ultraviolet absorption based sensor at 0.05 g m<sup>-3</sup> (O’Keeffe *et al.*, 2005c; O’Keeffe *et al.*, 2007) is higher than visible absorption based sensor at 5 g m<sup>-3</sup> (O’Keeffe *et al.*, 2005b) and 10 g m<sup>-3</sup> (O’Keeffe *et al.*, 2005c). Optical instrument purchase may be regarded as worthwhile investment for new research opportunities.

Based on the review, absorption based ozone sensor is found to be fast, reliable, safe to use and able to work at ambient temperature. Although absorption based ozone sensor may require high start up cost, it is a worthwhile investment for high ozone concentration measurement.

### **1.3 Problem Formulation**

From 2005 to 2012, researchers have adopted two methods to measure ozone concentration via ultraviolet absorption spectroscopy. Typically, researchers measure ozone concentration by non ratiometric method (O’Keeffe *et al.*, 2008; Degner *et al.*, 2009; Degner *et al.*, 2010; Aoyagi *et al.*, 2012). In this method, researchers compare intensities of absorbing wavelength that passes through ozone and does not pass

through ozone. Absorption cross section may be calculated using existing Beer–Lambert law when transmittance value is known. However, broadband light source typically experiences drift in output power of less than 0.01 % per hour (Ocean Optics, 2009). The drift in intensity affects stability of measurement. Alternatively, ratiometric method has been gaining popularity for ozone concentration measurement (O’Keeffe *et al.*, 2005a; O’Keeffe *et al.*, 2005b; O’Keeffe *et al.* 2005c; O’Keeffe *et al.*, 2007; Maria and Bartalesi, 2012; Maria and Rizzi, 2009; Maria *et al.*, 2008). In this method, researchers measure ozone concentration by comparing intensities of absorbing wavelength and non absorbing wavelength that pass through ozone. Ratiometric method helps to improve stability of measurement (O’Keeffe *et al.*, 2007), minimize system disturbances (O’Keeffe *et al.*, 2005b; O’Keeffe *et al.*, 2007), reduce particulate interference (O’Keeffe *et al.*, 2005a; O’Keeffe *et al.* 2005c), correct reference intensity drift (Maria *et al.*, 2008) and achieve linearity (Maria and Bartalesi, 2012). However, absorption cross section may not be calculated using existing Beer–Lambert law via ratiometric method, as transmittance value is not known. This is the reason absorption cross section is not explicitly reported in previous experiment via ratiometric method calculation (O’Keeffe *et al.*, 2005a; O’Keeffe *et al.*, 2005b; O’Keeffe *et al.* 2005c; O’Keeffe *et al.*, 2007; Maria and Bartalesi, 2012; Maria and Rizzi, 2009; Maria *et al.*, 2008). Based on literature review, measuring absorption cross section based on ratiometric method calculation may be considered as a novel technique. This is because a novel equation is to be established based on existing Beer–Lambert law for ratiometric method to calculate absorption cross section. The equation contributes to existing knowledge and benefits future researchers.

#### **1.4 Motivation of Research**

Measurement of ozone absorption cross section has attracted attention of researchers because the parameter is important for calculation of ozone concentration. Ultraviolet and visible absorption cross sections serve as vital reference for measuring atmospheric ozone gas via remote sensing (Orphal and Chance, 2003). Although ozone absorption cross section may be simulated online from spectralcalc.com based on HITRAN 2008 database, the simulation results are correct for ideal case at specific

temperature and pressure only. Actual experimental condition may not be similar to simulation or previous experimental conditions; thus, determination of absorption cross section parameter for each experiment ensures high accuracy calculation of ozone concentration. Increasing trend of adopting ratiometric method calculation for ozone concentration calculation has accelerated the need to determine absorption cross section through this method. Proper selection of sampling wavelength and optical path length help to preserve linearity of ozone concentration measurement. Verification of temperature and pressure dependence on ozone absorption cross section is important to ensure these parameters have minimal effect to ozone absorption cross section measurement.

### **1.5 Objectives of Research**

Based on formulation of problem and motivation of research, the objectives of this research are stated as follow:

1. To optimize range of ozone concentration measurement for specific optical path length of gas cell.
2. To illustrate deviation of Beer–Lambert law and propose a solution to maintain linearity of measurement.
3. To determine temperature and pressure stability of ozone absorption cross section.
4. To determine maximum ozone absorption cross section through ratiometric method at specific temperature and pressure.

## 1.6 Scope of Research

To achieve the objectives of this study, scope of research is divided into several categories as follow: theoretical study, preliminary simulation and experiment.

Theoretical study:

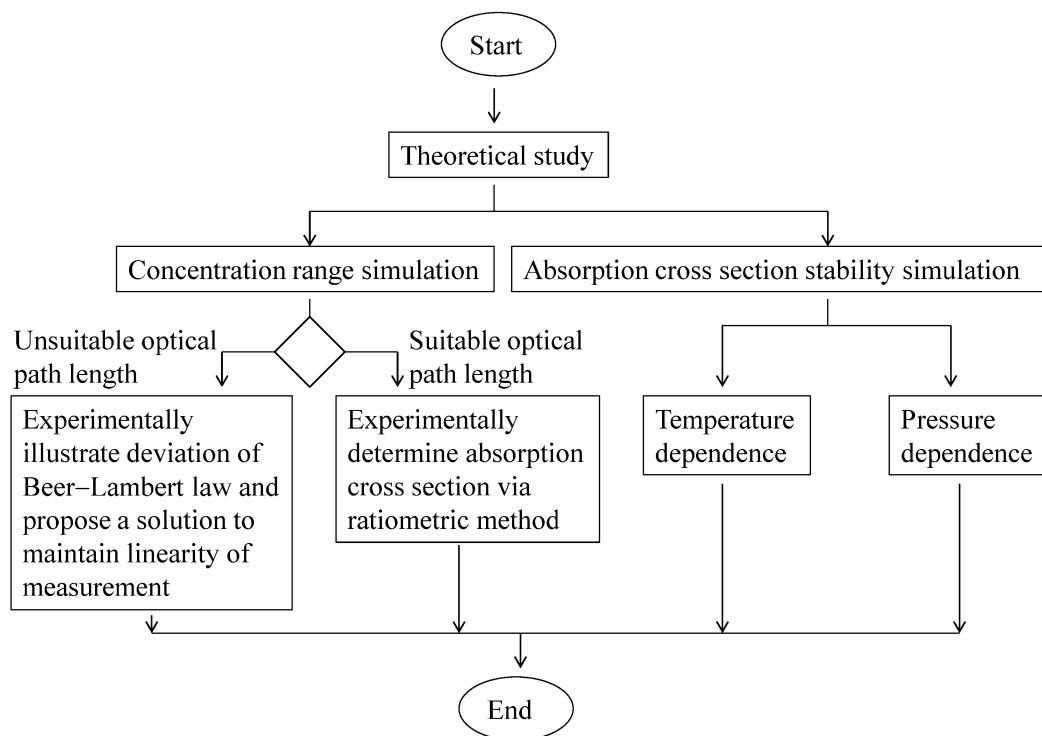
1. Mathematical relationships relevant to the study are derived and verified with literature. For example, a novel equation is established based on Beer–Lambert law for ozone absorption cross section measurement through ratiometric method. Relevant equations and relationship of conversion among units of concentration are derived in Appendix B. The concentration units are arranged to show variations of Beer–Lambert law and relations among important parameters. Mathematical relations established in this work are useful for future researchers to calculate desired parameters.

Simulations and experiments:

2. Simulate maximum absorption wavelength, maximum absorption cross section and practical dynamic range of ozone concentration measurement at optical path length 5 cm, 10 cm and 20 cm using spectralcalc.com gas cell simulator. This is to select optical path length of gas cell that suits ozone concentration measurement range of equipments in this work.
3. Perform experiment to determine linearity of Beer–Lambert law using gas cell of 10 cm optical path length. This is to illustrate deviation of Beer–Lambert law and propose a solution to prevent sensor saturation.
4. Simulate maximum absorption wavelength and maximum absorption cross section at temperature from 200 K to 300 K via spectralcalc.com line list browser. This is to verify temperature stability of wavelength used to measure ozone concentration.

5. Simulate maximum absorption wavelength and maximum absorption cross section at pressure from 0.1 atm to 3 atm via spectralcalc.com gas cell simulator. This is to verify pressure stability of wavelength used to measure ozone concentration.
6. Perform experiment to determine maximum absorption cross section via ratiometric method calculation. This is to improve stability of measurement, as ratiometric method corrects intensity drift of light source.

Further details are illustrated in Figure 1.1.



**Figure 1.1** Scope of research of this study

## 1.7 Overview of Thesis

Ratiometric method has been used to improve stability of measurement of ozone concentration in ultraviolet absorption spectroscopy. The method compensates

intensity drift of light source. However, ozone absorption cross section may not be determined via ratiometric method based on existing Beer–Lambert law. Absorption cross section defines strength of absorption, which is important for calculation of ozone concentration in ultraviolet absorption spectroscopy. Thus, this thesis proposes a novel technique to determine maximum ozone absorption cross section via ratiometric method. To achieve the objectives of this study, theoretical study, three simulations and two experiments have been conducted. These activities are organized into six chapters in this thesis as described below:

In chapter 1, ozone is introduced by discussing its physical properties and applications to highlight the need to measure ozone concentration. After that, ozone sensors are reviewed. Ultraviolet absorption spectroscopy is selected for ozone concentration measurement because the method is fast, reliable, safe to use, and able to measure high concentration at ambient temperature. Chapter 1 describes the need to conduct this study and highlights the approach that will be used for new knowledge creation.

Next, in chapter 2, theoretical background of absorption based ozone sensor is discussed. For example, equations are derived based on Beer–Lambert law for ozone concentration measurement in ppm by volume. In addition, Beer–Lambert law is modified so that a new equation may be applied for measurement of absorption cross section via ratiometric method. Conditions for Beer–Lambert law deviation is thoroughly discussed and supported by Twyman–Lothian equation. Hence, guidelines for adherence of Beer–Lambert law are discussed. In addition, characteristics of ozone absorption cross section are reviewed at different wavelengths and temperature. This is to justify the reason a particular wavelength is chosen for ozone concentration measurement. Performance specifications of absorption based ozone sensor are reviewed to obtain general relation among optical path length, dynamic range and response time. Chapter 2 describes fundamental measurement principles that are applicable at later part of this study.

Subsequently, in chapter 3, instrumentation for absorption based ozone sensor is reviewed. The review is important to decide equipments to be purchased and used in

this work. The review is categorized into optical components, gas components, and gas cell construction. Based on the review, gas cell is fabricated using ozone compatible materials. Details of fabrication will be discussed.

After that, in chapter 4, gas cell optical path length is optimized for high concentration measurement below 1000 ppm. This is because concentration up to 1000 ppm can be verified using 2B Technologies ozone monitor 106-M in this work. Spectralcalc.com gas cell simulator is used to relate optical path length and ozone concentration based on the assumption that transmittance lies between 0.25 and 0.5. The assumption is to avoid deviation of Beer–Lambert law as discussed in chapter 2. Next, experiment is conducted to illustrate limitation of long gas cell of 10 cm optical path length for high concentration below 1000 ppm. Extent of Beer–Lambert law deviation is characterized. After that, a solution is proposed to maintain linearity of measurement. As a result, short gas cell of 5 cm optical path length is applied in the next chapter for high concentration measurement below 1000 ppm.

Next, chapter 5 contains two simulations and one experiment to characterize ozone absorption cross section. Spectralcalc.com simulations are applied to verify temperature and pressure dependence on maximum ozone absorption cross section. After that, experiment is conducted to verify equation derived in chapter 2 to determine maximum ozone absorption cross section via ratiometric method. Significance of ratiometric method to compensate light source intensity drift is illustrated.

Finally, chapter 6 contains conclusions of study. Contributions of the study is discussed. Since research is a continuous effort, future work is suggested. Interested readers may refer to appendices for summary of ozone sensing techniques, conversion relations among concentration units and list of publications of this work.



## REFERENCES

- 2B Technologies (2010a). *Model 106-M Ozone Monitor Manual*. (Revision D). Colorado: 2B Technologies.
- 2B Technologies (2010b). *Model 106-L Ozone Monitor Manual*. (Revision E). Colorado: 2B Technologies.
- Abitan, H., Bohr, H. and Buchhave, P. (2008). Correction to the Beer–Lambert–Bouguer law for optical absorption. *Applied Optics*. 47(29), 5354–5357.
- Aday, M. S., Büyükcın, M. B., Temizkan, R. and Caner, C. (2014). Role of Ozone Concentrations and Exposure Times in Extending Shelf Life of Strawberry. *Ozone: Science & Engineering: The Journal of the International Ozone Association*. 36(1), 43–56.
- Aguir, K., Lemire, C. and Lollman, D. B. B. (2002). Electrical Properties of Reactively Sputtered WO<sub>3</sub> Thin Films as Ozone Gas Sensor. *Sensors and Actuators B: Chemical*. 84(1), 1–5.
- Allothman, M., Kaur, B., Fazilah, A., Bhat, R. and Karim, A. A. (2010). Ozone-induced Changes of Antioxidant Capacity of Fresh-cut Tropical Fruits. *Innovative Food Science and Emerging Technologies*. 11(4), 666–671.
- Aoyagi, Y., Takeuchi, M., Yoshida, K., Kurouchi, M., Araki, T., Nanishi, Y., Sugano, H., Ahiko, Y. and Nakamura, H. (2012). High-Sensitivity Ozone Sensing Using 280 nm Deep Ultraviolet Light-Emitting Diode for Detection of Natural Hazard Ozone. *Journal of Environmental Protection*. 3(8), 695–699.
- Arif, N. L. and Abdullah, A. M. (2011). Ozone Pollution and Historical Trends of Surface Background Ozone Level: A Review. *World Applied Sciences Journal*. 14(1), 31–38.
- Arshak, K., Hickey, G., Forde, E., and Harris, J. (2007). Development of Novel Room Temperature Ozone Sensors for Health and Safety Applications. *30th International Spring Seminar on Electronics Technology 2007 (ISSE 2007)*. 9–13 May. Cluj-Napoca, Romania: IEEE, 248–253.

- Asimov, I. (1955). The Composition of the Atmosphere. *Journal of Chemical Education*. 32(12), 633–634.
- Awad, M. B. and Castle, G. S. P. (1975). Ozone Generation in an Electrostatic Precipitator With a Heated Corona Wire. *Journal of the Air Pollution Control Association*. 25(4), 369–374.
- Axson, J. L., Washenfelder, R. A., Kahan, T. F., Young, C. J., Vaida, V. and Brown, S. S. (2011). Absolute Ozone Absorption Cross Section in the Huggins Chappuis Minimum (350–470 nm) at 296 K. *Atmospheric Chemistry and Physics*. 11, 11581–11590.
- Bass, A. M. and Paur, R. J. (1985). The Ultraviolet Cross-Sections of Ozone: I. The Measurements. In Zerefos, C. S. and Ghazi, A. (Eds.). *Atmospheric Ozone*. (pp. 606–610). Netherlands: Springer.
- Berry, L. and Hamwi, A. (2010). Activated- and Temperature-Controlled Carbon Filter to Avoid Interferences of Ozone and Nitrogen Dioxide on Semiconducting Gas Sensors. *Sensors and Actuators B: Chemical*. 150(2), 700–707.
- BMT MESSTECHNIK GMBH (2012). *TechNote TN-2: Ozone: Different "Concentrations"*. October 2012. Berlin, Germany: BMT MESSTECHNIK GMBH. Retrieved on April 7, 2014, from [bmt-berlin.com/TN2\\_Concentrations.pdf](http://bmt-berlin.com/TN2_Concentrations.pdf)
- Bo, Z., Lu, G., Wang, P. and Chen, J. (2013). Dimensional Analysis of Detrimental Ozone Generation by Negative Wire-to-Plate Corona Discharge in Both Dry and Humid Air. *Ozone: Science & Engineering: The Journal of the International Ozone Association*. 35(1), 31–37.
- Brion, J., Chakir, A., Charbonnier, J., Daumont, D., Parisse, C. and Malicet, J. (1998). Absorption Spectra Measurements for the Ozone Molecule in the 350–830 nm Region. *Journal of Atmospheric Chemistry*. 30(2), 291–299.
- Brion, J., Chakir, A., Daumont, D., Malicet, J. and Parisse, C. (1993). High-resolution Laboratory Absorption Cross Section of O<sub>3</sub>. Temperature Effect. *Chemical Physics Letters*. 213(5–6), 610–612.
- Brock, J. R. (1962). A Note on the Beer–Lambert Law. *Analytica Chimica Acta*. 27, 95–97.
- Brogren, M., Helgesson, A., Karlsson, B., Nilsson, J. and Roos, A. (2004). Optical Properties, Durability, and System Aspects of a New Aluminium-Polymer-

- Laminated Steel Reflector for Solar Concentrators. *Solar Energy Materials and Solar Cells*. 82(3), 387–412.
- Campbell, I. M. (1986). *Energy and the Atmosphere: A Physical-Chemical Approach*. (2<sup>nd</sup> ed.) (pp. 12, 14, 27, 45, 139). Chichester, England: John Wiley & Sons Ltd.
- Carotta, M. C., Cervi, A., Fioravanti, A., Gherardi, S., Giberti, A., Vendemiati, B., Vincenzi, D. and Sacerdoti, M. (2011). A Novel Ozone Detection at Room Temperature through UV-LED-Assisted ZnO Thick Film Sensors. *Thin Solid Films*. 520(3), 939–946.
- Castle, G. S. P., Incelet, I. and Burgess, K. I. (1969). Ozone Generation in Positive Corona Electrostatic Precipitators. *IEEE Transactions on Industry and General Applications*. IGA-5(4), 489-496.
- Chen, H., Stanier, C. O., Young, M. A. and Grassian, V. H. (2011). A Kinetic Study of Ozone Decomposition on Illuminated Oxide Surfaces. *The Journal of Physical Chemistry A*. 115(43), 11979–11987.
- Chien, F. S. S., Wang, C. R., Chan, Y. L, Lin, H. L., Chen, M. H. and Wu, R. J. (2010). Fast-Response Ozone Sensor with ZnO Nanorods Grown by Chemical Vapor Deposition. *Sensors and Actuators B: Chemical*. 144(1), 120–125.
- Clark, B. J., Frost, T. and Russell, M. A. (1993). *Techniques in Visible and Ultraviolet Spectrometry Volume 4: UV Spectroscopy, Techniques, Instrumentation, Data Handling*. (1<sup>st</sup> ed.) (pp. 6, 8, 47–51, 65). Boundary Row, London: Chapman & Hall.
- Conde, O. M., Garc ía, S., Mirapeix, J. M., Echevarr ía, J., Madruga, F. J. and López-Higuera, J. M. (2011). New Optical Cell Design for Pollutant Detection. *Proceedings of SPIE—The International Society for Optical Engineering*. Fiber Optic Sensor Technology and Applications 2011. 30 October–1 November. Newton, Massachusetts: SPIE, 4578, 283–290.
- Cooper, O. R., Parrish, D. D., Stohl, A., Trainer, M., Nédéc, P., Thouret, V., Cammas, J. P., Oltmans, S. J., Johnson, B. J., Tarasick, D., Leblanc, T., McDermid, I. S., Jaffe, D., Gao, R., Stith, J., Ryerson, T., Aikin, K., Campos, T., Weinheimer, A. and Avery, M. A. (2010). Increasing Springtime Ozone Mixing Ratios in the Free Troposphere over Western North America. *Nature*. 463, 344–348.

- Daumont, D., Brion, J., Charbonnier, J. and Malicet, J. (1992). Ozone UV Spectroscopy I: Absorption Cross-Sections at Room Temperature. *Journal of Atmospheric Chemistry*. 15(2), 145–155.
- Department of Occupational Safety and Health (2010). *Industry Code of Practice on Indoor Air Quality 2010*. (pp. 11). Malaysia: Department of Occupational Safety and Health, Ministry of Human Resources. Retrieved on November 12, 2014, from [www.dosh.gov.my/images/dmdocuments/CodeOfPractice/ve\\_cop\\_iaq\\_2010.zip](http://www.dosh.gov.my/images/dmdocuments/CodeOfPractice/ve_cop_iaq_2010.zip)
- Degner, M., Damaschke, N., Ewald, H. and Lewis, E. (2010). High Resolution LED-Spectroscopy for Sensor Application in Harsh Environment: A Sensor System Based on LED-light Sources and Standard Photodiode Receiver is Shown as an Example of This Sensor Concept for In-situ Gas Measurements Down to the ppb Range. *Proceedings of IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*. 3–6 May. Austin, Texas: IEEE, 1382–1386.
- Degner, M., Damaschke, N., Ewald, H., O’Keeffe, S., and Lewis, E. (2009). UV LED-Based Fiber Coupled Optical Sensor for Detection of Ozone in the ppm and ppb Range. *Proceedings of IEEE Sensors Conference (SENSORS 2009)*. 25–28 October. Christchurch, New Zealand: IEEE, 95–99.
- Dieck, R. H. (1999). *Measurement Accuracy*. In Webster, J. G. (Ed.). *The Measurement, Instrumentation and Sensors Handbook*. (pp. 4-1 to 4-13). Boca Raton, Florida: CRC Press Taylor & Francis Group.
- Domnin, P. I. and Chelibanov, V. P. (1997). Accuracy and Operating Characteristics of Instruments for Ozone Content Measurements in the Atmosphere. *Proceedings of SPIE–The International Society for Optical Engineering*. 23rd European Meeting on Atmospheric Studies by Optical Methods. 3 September. Kiev, Ukraine: SPIE, 3237, 54–61.
- Dooly, G. (2008). *On-Board Monitoring of Vehicle Exhaust Emissions Using an Ultraviolet Optical Fibre Based Sensor*. (pp. 153). Thesis of Doctor of Philosophy, University of Limerick, Ireland.
- Dooly, G., Mulrooney, J., Merlone-Borla, E., Flavia, G., Clifford, J., Fitzpatrick, C. and Lewis, E. (2008). In-Situ Monitoring of Carbon Dioxide Emissions from a Diesel Automobile using a Mid-Infrared Optical Fibre Based Point Sensor. *Proceedings of IEEE Instrumentation and Measurement Technology Conference (I2MTC)*. 12–15 May. Victoria, British Columbia: IEEE, 1891–1894.

- Facta, M., Salam, Z. and Buntat, Z. (2009) The Development of Ozone Generation with Low Power Consumption. *Proceedings of Conference on Innovative Technologies in Intelligent Systems and Industrial Applications (CITISIA 2009)*. 25–26 July. Monash University, Sunway Campus, Malaysia: IEEE, 440–445.
- Facta, M., Salam, Z., Jusoh, A. and Buntat, Z. (2008). Improvement in Ozone Generation with Low Voltage High Frequency Power Converters. *Proceedings of IEEE 2nd International Power and Energy Conference (PECon 2008)*. 1–3 December. Johor Bahru, Malaysia: IEEE, 1446–1450.
- Fuwa, K. and Valle, B. L. (1963). The Physical Basis of Analytical Atomic Absorption Spectrometry. The Pertinence of the Beer–Lambert Law. *Analytical Chemistry*. 35(8), 942–946.
- Gabriolotto, C., Monchiero, M., Negre, M., Spadaro, D. and Gullino, M. L. (2009). Effectiveness of Control Strategies Against Botrytis Cinerea in Vineyard and Evaluation of the Residual Fungicide Concentrations. *Journal of Environmental Science and Health–Part B Pesticides, Food Contaminants, and Agricultural Wastes*. 44(4), 389–396.
- Ghaddab, B., Sanchez, J. B., Mavon, C., Paillet, M., Parret, R., Zahab, A. A., Bantignies, J. L., Flaud, V., Beche, E. and Berger, F. (2012). Detection of O<sub>3</sub> and NH<sub>3</sub> Using Hybrid Tin Dioxide/Carbon Nanotubes Sensors: Influence of Materials and Processing on Sensor's Sensitivity. *Sensors and Actuators B: Chemical*. 170, 67–74.
- Gorshelev, V. and Serdyuchenko, A. (2011). *Absorption Spectroscopy of Atmospheric Species (Ozone)*. Molecular Spectroscopy Laboratory, University of Bremen. Retrieved on June 10, 2013, from [www.msc-ep.uni-bremen.de/services/lectures/practicals/pr\\_ozone\\_ss2011.pdf](http://www.msc-ep.uni-bremen.de/services/lectures/practicals/pr_ozone_ss2011.pdf)
- Gottschalk, C., Libra, J. A. and Saupe, A. (2010). *Ozonation of Water and Waste Water: a Practical Guide to Understanding Ozone and its Applications*. (2<sup>nd</sup> ed.) (pp. 9, 111). Weinheim: Wiley-VCH Verlag GmbH & Co. KGaA.
- Griggs, M. (1968). Absorption Coefficients of Ozone in the Ultraviolet and Visible Regions. *The Journal of Chemical Physics*. 49(2), 857–859.
- Haas, T., Lammers, P. S., Diekmann, B., Horner, G. and Boeker, P. (2008). A Method for Online Measurement of Odour with a Chemosensor System. *Sensors and Actuators B: Chemical*. 132(2), 545–550.

- Hadji, K., Pontiga, F., Belasri, A., Hadj-Ziane, S. and Fernández-Rueda, A. (2014). Experimental Study of Ozone Generation by Negative Corona Discharge in Mixtures of N<sub>2</sub> and O<sub>2</sub>. *Ozone: Science & Engineering: The Journal of the International Ozone Association*. 36(1), 65–72.
- Hamamatsu (2008). *Application Circuit Examples of Si Photodiode*. Hamamatsu City, Japan: Hamamatsu. Retrieved on March 25, 2014, from [www.hamamatsu.com/resources/pdf/ssd/si\\_pd\\_circuit\\_e.pdf](http://www.hamamatsu.com/resources/pdf/ssd/si_pd_circuit_e.pdf)
- Hamamatsu (2014). *Si Photodiode S12742-254*. Hamamatsu City, Japan: Hamamatsu. Retrieved on March 25, 2014, from [www.hamamatsu.com/resources/pdf/ssd/s12742-254\\_kspd1082e01.pdf](http://www.hamamatsu.com/resources/pdf/ssd/s12742-254_kspd1082e01.pdf)
- Han, Y., Liang, T., Yang, X., Ren, X. and Yi, Y. (2010). Research on Optical Air Chamber of Infrared Gas Sensor. *First International Conference on Pervasive Computing, Signal Processing and Applications*. 17–19 September. Harbin, China: IEEE, 33–36.
- Hansman, R. J. (1999). *Characteristics of Instrumentation*. In Webster, J. G. (Ed.), *The Measurement, Instrumentation and Sensors Handbook*. (pp. 1-1 to 1-8). Boca Raton, Florida: CRC Press Taylor & Francis Group.
- Hearn, A. G. (1961). The Absorption of Ozone in the Ultra-violet and Visible Regions of the Spectrum. *Proceedings of the Physical Society*. 78(5), 932–940.
- Hof, M. (2003). *Basics of Optical Spectroscopy*. In Gauglitz, G. and Vo-Dinh, T. (Eds.). *Handbook of Spectroscopy*. (pp. 39–47). Weinheim, Germany: WILEY-VCH Verlag GmbH & Co. KGaA.
- Holman, J. P. (2012). *Experimental Methods for Engineers*. (8<sup>th</sup> ed.) (pp. 5, 586, 595). Manhattan, New York: McGraw-Hill.
- Horvath, H. (1988). Experimental Investigation on the Validity of the Lambert–Beer Law at High Particle Concentrations. *Journal of Aerosol Science*. 19(7), 837–840.
- Horvitz, S. and Cantalejo, M. J. (2012). Effects of Ozone and Chlorine Postharvest Treatments on Quality of Fresh-cut Red Bell Peppers. *International Journal of Food Science and Technology*. 47(9), 1935–1943.
- Hughes, H. K. (1963). Beer's Law and the Optimum Transmittance in Absorption Measurements. *Applied Optics*. 2(9), 937–945.
- Inn, E. C. Y. and Tanaka, Y. (1953). Absorption Coefficient of Ozone in the Ultraviolet and Visible Regions. *Journal of the Optical Society of America*. 43(10), 870–873.

- Jakpor, O. (2009). Pulmonary Effects of Ozone-Generating Air Purifiers. *Young Scientists Journal*. 2(7): 20–31.
- Janssen, C., Simone, D. and Guinet, M. (2011). Preparation and Accurate Measurement of Pure Ozone. *Review of Scientific Instruments*. 82(3), 034102-1 to 034102-10.
- Karaca, H., Walse, S. S. and Smilanick, J. L. (2012). Effect of Continuous 0.3 mL/L Gaseous Ozone Exposure on Fungicide Residues on Table Grape Berries. *Postharvest Biology and Technology*. 64(1), 154–159.
- Köhring, M., Willer, U., Böttger, S., Pohlkötter, A. and Schade, W. (2012). Fiber-Coupled Ozone Sensor Based on Tuning Fork-Enhanced Interferometric Photoacoustic Spectroscopy. *IEEE Journal of Selected Topics in Quantum Electronics*. 18(5), 1566–1572.
- Koike, K., Inoue, G. and Fukuda, T. (1999). Explosion Hazard of Gaseous Ozone. *Journal of Chemical Engineering of Japan*. 32(3), 295–299.
- Lake, L. R. (2001). Secondary Direct Food Additives Permitted in Food for Human Consumption. *Federal Register*. 26 June 2001. United States Food and Drug Administration, Department of Health and Human Services. 66(123), 33829–33830. Retrieved on May 28, 2013, from <http://www.fda.gov/OHRMS/Dockets/98fr/062601a.htm>
- Larsen, M. L. and Clark, A. S. (2014). On the Link between Particle Size and Deviations from the Beer–Lambert–Bouguer Law for Direct Transmission. *Journal of Quantitative Spectroscopy and Radiative Transfer*. 133, 646–651.
- Li, S., Timoshkin, I. V., Maclean, M., MacGregor, S. J., Wilson, M. P., Given, M. J., Anderson, J. G. and Wang, T. (2013). Steady-State Corona Discharges in Atmospheric Air for Cleaning and Decontamination. *IEEE Transactions on Plasma Science*. 41(10), 2871–2878.
- Longevity Resources (2014). *EXT50 Ozone Generator 220/240 Volt Owner's Manual and Ozone Output Test Report*. 8 January 2014. Sidney, British Columbia: Longevity Resources.
- Maikala, R. V. (2010). Modified Beer's Law—Historical Perspectives and Relevance in Near-infrared Monitoring of Optical Properties of Human Tissue. *International Journal of Industrial Ergonomics*. 40(2), 125–134.

- Malicet, J., Daumont, D., Charbonnier, J., Parisse, C., Chakir, A. and Brion, J. (1995). Ozone UV Spectroscopy. II. Absorption Cross-Sections and Temperature Dependence. *Journal of Atmospheric Chemistry*. 21(3), 263–273.
- Manap, H. (2011). *An Ultra Violet Optical Fibre Based Sensor for Ammonia Detection in the Agricultural Sector*. (pp. 126). Thesis of Doctor of Philosophy, University of Limerick, Ireland.
- Manap, H., Muda, R., O’Keeffe, S. and Lewis, E. (2009). Ammonia Sensing and a Cross Sensitivity Evaluation with Atmosphere Gases using Optical Fiber Sensor. *Procedia Chemistry*. 1(1), 959–962.
- Manning, T. J. (2000). Production of Ozone in an Electrical Discharge using Inert Gas as Catalysts. *Ozone: Science & Engineering: The Journal of the International Ozone Association*. 22(1), 53–64.
- Maria, L. D. and Bartalesi, D. (2012). A Fiber-Optic Multisensor System for Predischarges Detection on Electrical Equipment. *IEEE Sensors Journal*. 12(1), 207–212.
- Maria, L. D. and Rizzi, G. (2009). Ozone Sensor for Application in Medium Voltage Switchboard. *Journal of Sensors*. 2009, 1–5.
- Maria, L. D., Rizzi, G., Serragli, P., Marini, R. and Fialdini, L. (2008). Optical Sensor for Ozone Detection in Medium Voltage Switchboard. *Proceedings of IEEE Sensors Conference (SENSORS 2008)*. 26–29 October. Lecce, Italy: IEEE, 1297–1300.
- Martins, R., Fortunato, E., Nunes, P., Ferreira, I., Marques, A., Bender, M., Katsarakis, N., Cimalla, V. and Kiriakidis, G. (2004). Zinc Oxide as an Ozone Sensor. *Journal of Applied Physics*. 96(3), 1398–1408.
- Maruo, Y. Y. (2007). Measurement of Ambient Ozone using Newly Developed Porous Glass Sensor. *Sensors and Actuators B: Chemical*. 126(2), 485–491.
- Maruo, Y. Y., Akaoka, K. and Nakamura, J. (2010). Development and Performance Evaluation of Ozone Detection Paper Using Azo Dye Orange I: Effect of pH. *Sensors and Actuators B: Chemical*. 143(2), 487–493.
- Maruo, Y. Y., Kunioka, T., Akaoka, K. and Nakamura, J. (2009). Development and Evaluation of Ozone Detection Paper. *Sensors and Actuators B: Chemical*. 135(2), 575–580.
- Matsumi, Y. and Kawasaki, M. (2003). Photolysis of Atmospheric Ozone in the Ultraviolet Region. *Chemical Review*. 103(12), 4767–4782.



- Mayrwöger, J., Reichl, W., Hauer, P., Krutzler, C. and Jakoby, B. (2009). Design and Simulation of a NDIR Gas Sensor System with Ray Tracing Using a Monte-Carlo Method. *Proceedings of Sensor+Test Conference 2009 - IRS<sup>2</sup> 2009*. 26–28 May. Nuremberg, Germany: AMA Service GmbH, 263–268.
- McClurkin, J. D., Maier, D. E. and Iteleji, K. E. (2013). Half-life Time of Ozone as a Function of Air Movement and Conditions in a Sealed Container. *Journal of Stored Products Research*. 55, 41–47.
- Mellqvist, J. and Rosén, A. (1996). DOAS for Flue Gas Monitoring—II. Deviations from the Beer–Lambert law for the U.V./visible Absorption Spectra of NO, NO<sub>2</sub>, SO<sub>2</sub> and NH<sub>3</sub>. *Journal of Quantitative Spectroscopy and Radiative Transfer*. 56(2), 209–224.
- Mennad, B., Harrache, Z., Aid, D. A. and Belasri, A. (2010). Theoretical Investigation of Ozone Production in Negative Corona Discharge. *Current Applied Physics*. 10(6), 1391–1401.
- Mikoviny, T., Skalny, J. D., Orszagh, J. and Mason, N. J. (2007). The Role of Water and Oxygen Impurities on Ozone Production in a Negative Corona Discharge of CO<sub>2</sub>. *Journal of Physics D: Applied Physics*. 40(21), 6646–6650.
- Miwa, T., Maruo, Y. Y., Akaoka, K., Kunioka, T. and Nakamura, J. (2009). Development of Colorimetric Ozone Detection Papers with High Ultraviolet Resistance Using Ultraviolet Absorbers. *Journal of the Air and Waste Management Association*. 59(7), 801–808.
- Naitou, S. and Takahara, H. (2008). Recent Developments in Food and Agricultural uses of Ozone as an Antimicrobial Agent-Food Packaging Film Sterilizing Machine using Ozone. *Ozone: Science and Engineering: The Journal of the International Ozone Association*. 30(1), 81–87.
- Nakagawa, H., Okazaki, S., Asakura, S., Shimizu, H. and Iwamoto, I. (2001). A New Ozone Sensor for an Ozone Generator. *Sensors and Actuators B: Chemical*. 77(1–2), 543–547.
- Naya, K. and Okada, F. (2012). Effects of NaCl and Na<sub>2</sub>SO<sub>4</sub> Cathode Electrolytes on Electrochemical Ozone Production. *Electrochimica Acta*. 78, 495–501.
- O’Keefe, S. (2006). *Spectroscopic Sensing Measurements Using Polymer Optical Fibres for Applications in the Sterilisation Industry*. (pp. 26). Thesis of Doctor of Philosophy, University of Limerick, Ireland.

- O'Keefe, S., Dooly, G., Fitzpatrick, C. and Lewis, E. (2005c). Optical Fibre Sensor for the Measurement of Ozone. *Journal of Physics: Conference Series*. Sensors and Their Applications XIII 2005. 6–8 September. Kent, United Kingdom: Institute of Physics Publishing, 15, 213–218.
- O'Keefe, S., Fitzpatrick, C. and Lewis, E. (2007). An Optical Fibre Based Ultra Violet and Visible Absorption Spectroscopy System for Ozone Concentration Monitoring. *Sensors and Actuators B: Chemical*. 125(2), 372–378.
- O'Keefe S., Fitzpatrick C. and Lewis E. (2005a). Ozone Measurement Using an Optical Fibre Sensor in the Visible Region. *Proceedings of IEEE Sensors Conference*. 31 October–3 November. Irvine, California: IEEE, 758–761.
- O'Keefe, S., Fitzpatrick, C. and Lewis, E. (2005b). Ozone Measurement in Visible Region: an Optical Fibre Sensor System. *Electronics Letters*. 41(24), 1317–1319.
- O'Keefe, S., Ortoneda, M., Cullen, J. D., Shaw, A., Phipps, D., Al-Shamma'a, A. I., Fitzpatrick, C. and Lewis, E. (2008). Development of an Optical Fibre Sensor System for Online Monitoring of Microwave Plasma UV and Ozone Generation System. *Proceedings of IEEE Sensors Conference (SENSORS 2008)*. 26–29 October. Lecce, Italy: IEEE, 454–457.
- Ocean Optics (2008). *HR4000 and HR4000CG-UV-NIR Series High-Resolution Fiber Optic Spectrometers Installation and Operation Manual*. Dunedin, Florida: Ocean Optics. Retrieved on February 17, 2014, from [www.oceanoptics.com/technical/hr4000.pdf](http://www.oceanoptics.com/technical/hr4000.pdf)
- Ocean Optics (2009). *Operating Instructions Deuterium-Halogen Light Source*. Ostfildern, Germany: Ocean Optics GmbH.
- Ocean Optics (2012). *Catalog of Products Spectrometers, Accessories and More*. Dunedin, Florida: Ocean Optics.
- Ocean Optics (2013). *74-UV, 74-Vis Collimating Lenses, Operating Instructions: Collimating Lenses*. Dunedin, Florida: Ocean Optics. Retrieved on September 2, 2013, from [www.oceanoptics.com/Technical/collimatinglenses.pdf](http://www.oceanoptics.com/Technical/collimatinglenses.pdf)
- Orphal, J. and Chance, K. (2003). Ultraviolet and Visible Absorption Cross-sections for HITRAN. *Journal of Quantitative Spectroscopy and Radiative Transfer*. 82(1–4), 491–504.
- Ozone Services (2013). *Material Compatibility with Ozone*. Burton, Canada: Ozone Services. Retrieved on July 24, 2013, from <http://www.ozoneservices.com/articles/003.htm>

- Ozone Solutions (2013). *Ozone Compatible Materials*. Hull, Iowa: Ozone Solutions. Retrieved on July 24, 2013, from <http://www.ozonesolutions.com/info/ozone-compatible-materials>
- Ozone Solutions (2014). *Ozone Compatible Flowmeters*. Hull, Iowa: Ozone Solutions. Retrieved on June 16, 2014, from <http://www.ozonesolutions.com/products/Flow-Meters>
- Pacific Ozone (2013). *Material Compatibility with Ozone*. Benecia, California: Pacific Ozone. Retrieved online on July 24, 2013, from [www.pacificozone.com/PDF/MaterialCompatibility%20withOzone.pdf](http://www.pacificozone.com/PDF/MaterialCompatibility%20withOzone.pdf)
- Paldus, B. A. and Kachanov, A. A. (2005). An Historical Overview of Cavity-Enhanced Methods. *Canadian Journal of Physics*. 83(10), 975–999.
- Park, Y., Dong, K. Y., Lee, J., Choi, J., Bae, G. N. and Ju, B. K. (2009). Development of an Ozone Gas Sensor using Single-walled Carbon Nanotubes. *Sensors and Actuators B: Chemical*. 140(2), 407–411.
- Parnis, J. M. and Oldham, K. B. (2013). Beyond the Beer–Lambert Law: The Dependence of Absorbance on Time in Photochemistry. *Journal of Photochemistry and Photobiology A: Chemistry*. 267, 6–9.
- Pekárek, S. (2008). Ozone Production by a DC Corona Discharge in Air Contaminated by n-Heptane. *Journal of Physics D: Applied Physics*. 41(2), 1–6.
- Penru, Y., Guastalli, A. R., Esplugas, S. and Baig, S. (2013). Disinfection of Seawater: Application of UV and Ozone. *Ozone: Science & Engineering: The Journal of the International Ozone Association*. 35(1), 63–70.
- Pontiga, F., Soria, C., Castellanos, A. and Skalny, J. D. (2002). A Study of Ozone Generation by Negative Corona Discharge Through Different Plasma Chemistry Models. *Ozone: Science & Engineering: The Journal of the International Ozone Association*. 24(6), 447–462.
- Puschell, J. J., Hastings, C. T., Chrien, T., Larar, A. M., Cook, W. B., Mills, C. S., Flood, M. A. and Skinner, W. R. (2005). Trace Tropospheric Species Sensing-Fabry-Perot-Interferometer (TTSS-FPI): Spaceborne Sensor Concept Studies for Measuring Tropospheric Ozone. *Proceedings of SPIE–The International Society for Optical Engineering*. Multispectral and Hyperspectral Remote Sensing Instruments and Applications II. 20 January. Bellingham, Washington: SPIE, 5655, 181–189.

- Rajab, J. M., MatJafri, M. Z., Lim, H. S. and Abdullah, K. (2010). Daily Distribution Map of Ozone (O<sub>3</sub>) from AIRS over Southeast Asia. *Energy Research Journal* 1(2), 158–164.
- Rajab, J. M., MatJafri, M. Z., Tan, F., Lim, H. S. and Abdullah, K. (2011). Analysis of Ozone Column Burden in Peninsular Malaysia Retrieved from Atmosphere Infrared Sounder (AIRS) Data: 2003-2009. *Proceedings of IEEE International Imaging Systems and Techniques (IST) Conference*. Penang, Malaysia: IEEE, 29–33.
- Rivas, J., Gimeno, O. and Beltrán, F. (2009) Wastewater Recycling: Application of Ozone Based Treatments to Secondary Effluent. *Chemosphere*. 74(6), 854–859.
- Saakov, V. S., Drapkin, V. Z., Krivchenko, A. I., Rozengart, E. V., Bogachev, Y. V. and Knyazev, M. N. (2013). *Basis of Derivative Spectrophotometry*. In Saakov, V. S., Drapkin, V. Z., Krivchenko, A. I., Rozengart, E. V., Bogachev, Y. V. and Knyazev, M. N. (Eds.). *Derivative Spectrophotometry and Electron Spin Resonance (ESR) Spectroscopy for Ecological and Biological Questions*. (pp. 6, 7, 14). Wien, Austria: Springer-Verlag. Retrieved on September 26, 2013, from [link.springer.com/content/pdf/10.1007%2F978-3-7091-1007-2.pdf](http://link.springer.com/content/pdf/10.1007%2F978-3-7091-1007-2.pdf)
- Sano, N. and Ohtsuki, F. (2007). Carbon Nanohorn Sensor to Detect Ozone in Water. *Journal of Electrostatics*. 65(4), 263–268.
- Shah, N. N. A. K., Rahman, R. A., Chuan, L. T. and Hashim, D. M. (2011). Application of Gaseous Ozone to Inactive Bacillus Cereus in Processed Rice. *Journal of Food Process Engineering*. 34(6), 2220–2232.
- Siano, S. A. (1993). A Simple Method of Correction for Forward Rayleigh Scattering in Turbidity Measurements. *Applied Optics*. 32(24), 4646–4651.
- Skalný, J. D., Országh, J., Matejčík, Š. and Mason, N. J. (2008). Ozone Generation in Positive and Negative Corona Discharge Fed by Humid Oxygen and Carbon Dioxide. *Physica Scripta T*. 12th Latin American Workshop on Plasma Physics. 17–21 September 2007. Caracas, Venezuela: Institute of Physics Publishing, T131, 1–3.
- Sonntag, C. V. and Gunten, U. V. (2012). *Chemistry of Ozone in Water and Wastewater Treatment*. (pp. 3, 4, 10). London, United Kingdom: The International Water Association Publishing.

- Spartan Environmental Technologies (2013). *Ozone Measurement Units*. Beachwood, Ohio: Spartan Environmental Technologies. Retrieved on June 6, 2013, from <http://www.spartanwatertreatment.com/ozone-measurement-units.html>
- Spectralcalc.com High-Resolution Spectral Modeling*. Newport News, Virginia: GATS Inc. Retrieved on April 5, 2013, from <http://www.spectralcalc.com/info/about.php>
- Steiner, G. (2003). *Measurement Techniques*. In Gauglitz, G. and Vo-Dinh, T. (Eds.). *Handbook of Spectroscopy*. (pp. 70–88). Weinheim, Germany: WILEY-VCH Verlag GmbH & Co. KGaA.
- Tejerina, B. (2009). *UV/Vis Spectra simulator*. Retrieved on March 30, 2013, from <https://nanohub.org/resources/uvspec>. (DOI: 10.4231/D32R3NW8V)
- Teranishi, K., Shimada, Y., Shimomura, N. and Itoh, H. (2013). Investigation of Ozone Concentration Measurement by Visible Photo Absorption Method. *Ozone: Science & Engineering: The Journal of the International Ozone Association*. 35(3), 229–239.
- Tiwari, B. K. and Muthukumarappan, K. (2012). *Ozone in Fruit and Vegetable Processing*. In O'Donnell, C., Tiwari, B. K., Cullen, P. J. and Rice, R. G. (Eds.). *Ozone in Food Processing*. (pp. 55–80). Hoboken, New Jersey: Wiley-Blackwell.
- Torrents, A., Damera, R., Hao, O. J. (1997). Low-temperature Thermal Desorption of Aromatic Compounds from Activated Carbon. *Journal of Hazardous Materials*. 54(3), 141–153.
- Tseng, C. and Li, C. (2008). Inactivation of Surface Viruses by Gaseous Ozone. *Journal of Environment Health*. 70(10), 56–62.
- United States Department of Health and Human Services and United States Department of Labour (1978). *Occupational Health Guideline for Ozone*. United States Department of Health and Human Services and United States Department of Labour. Retrieved on June 16, 2014, from [www.cdc.gov/niosh/docs/81-123/pdfs/0476.pdf](http://www.cdc.gov/niosh/docs/81-123/pdfs/0476.pdf)
- United States Environmental Protection Agency (2003). *Ozone, Good Up High, Bad Nearby*. Washington, District of Columbia: Office of Air and Radiation, United States Environmental Protection Agency. Retrieved on May 28, 2013, from [www.epa.gov/airnow/gooduphigh/ozone.pdf](http://www.epa.gov/airnow/gooduphigh/ozone.pdf)
- Venta, M. B., Broche, S. S. C., Torres, I. F., Pérez, M. G., Lorenzo, E. V., Rodriguez, Y. R. and Cepero, S. M. (2010). Ozone Application for Postharvest Disinfection of

- Tomatoes. *Ozone: Science & Engineering: The Journal of the International Ozone Association*. 32(5), 361–371.
- Viallon, J., Moussay, P., Norris, J. E., Guenther, F. R. and Wielgosz, R. I. (2006). A Study of Systematic Biases and Measurement Uncertainties in Ozone Mole Fraction Measurements with the NIST Standard Reference Photometer. *Metrologia*. 43(5), 441–450.
- Vijayan, T. and Patil, J. G. (2011). Temporal Development of Ozone Generation in Electron-induced Corona-discharge Plasma. *IEEE Transactions on Plasma Science*. 39(11 Part 3), 3168–3172.
- Voigt, S., Orphal, J., Bogumil, K. and Burrows, J. P. 2001. The Temperature Dependence (203–293 K) of the Absorption Cross Sections of O<sub>3</sub> in the 230–850 nm Region Measured by Fourier-transform Spectroscopy. *Journal of Photochemistry and Photobiology A: Chemistry*. 143(1), 1–9.
- Wagner, T., Hennemann, J., Kohl, C. D. and Tiemann, M. (2011). Photocatalytic Ozone Sensor based on Mesoporous Indium Oxide: Influence of the Relative Humidity on the Sensing Performance. *Thin Solid Films*. 520(3), 918–921.
- Wallner, F. (2009). *TechNote TN-1: High Concentration Photometric Ozone Measurement Palimpsest*. Berlin, Germany: BMT MESSTECHNIK GMBH. Retrieved on August 20, 2013, from [www.bmt-berlin.com/ozone\\_handbook.pdf](http://www.bmt-berlin.com/ozone_handbook.pdf)
- Wallner, F. (2013). *Calibration and Recalibration of BMT Ozone Photometers*. 21 May 2013. Berlin, Germany: BMT MESSTECHNIK GMBH.
- Wang, C. Y., Becker, R. W., Passow, T., Pletschen, W., Köhler, K., Cimalla, V. and Ambacher, O. (2011). Photon Stimulated Sensor Based on Indium Oxide Nanoparticles I: Wide-concentration-range Ozone Monitoring in Air. *Sensors and Actuators B: Chemical*. 152(2), 235–240.
- Wang, P. and Chen, J. (2009). Numerical Modelling of Ozone Production in a Wire–cylinder Corona Discharge and Comparison with a Wire–plate Corona Discharge. *Journal of Physics D: Applied Physics*. 42(3), 1–8.
- Washenfelder, R. A., Wagner, N. L., Dube, W. P. and Brown, S. S. (2011). Measurement of Atmospheric Ozone by Cavity Ring-down Spectroscopy. *Environmental Science & Technology*. 45(7), 2938–2944.
- Weschler, C. J. (2000). Ozone in Indoor Environments: Concentration and Chemistry. *Indoor Air International Journal of Indoor Environment and Health*. 10(4), 269–288.

- Wind, L. and Szymanski, W. W. (2002). Quantification of Scattering Corrections to the Beer–Lambert Law for Transmittance Measurements in Turbid Media. *Measurement Science and Technology*. 13(3), 270–275.
- Yadav, R., Sahu, L. K., Jaaffrey, S. N. A. and Beig, G. (2014). Distributions of Ozone and Related Trace Gases at an Urban Site in Western India. *Journal of Atmospheric Chemistry*. 71(2), 125–144.
- Yagi, S. and Tanaka, M. (1978). Mechanism of Ozone Generation in Air-fed Ozonisers. *Journal of Physics D: Applied Physics*. 12(9), 1509–1520.
- Yanallah, K., Pontiga, F. and Castellanos, A. (2011). Numerical Simulation of an Oxygen-fed wire-to-cylinder Negative Corona Discharge in the Glow Regime. *Journal of Physics D: Applied Physics*. 44(5), 1–14.
- Yanallah, K., Pontiga, F., Fernández-Rueda, A. and Castellanos, A. (2009). Experimental Investigation and Numerical Modelling of Positive Corona Discharge: Ozone Generation. *Journal of Physics D: Applied Physics*. 42(6), 1–8.
- Yanallah, K., Pontiga, F., Meslem, Y. and Castellanos, A. (2012). An Analytical Approach to Wire-to-cylinder Corona Discharge. *Journal of Electrostatics*. 70(4), 374–383.
- Yang, Q., Pehkonen, S. O. and Ray, M. B. (2005). Performance Evaluation of Light Emission Models in Light Attenuating Media. *Ozone: Science & Engineering: The Journal of the International Ozone Association*. 27(6), 459–467.
- Yasin, M., Harun, S. W., Tan, C. F., Phang, S. W. and Ahmad, H. (2011). Fiber Optic Chemical Sensor using Fiber Coupler Probe based on Intensity Modulation for Alcohol Detection. *Microwave and Optical Technology Letters*. 53(8), 1935–1938.
- Yehia, A. and Mizuno, A. (2013). Ozone Generation by Negative Direct Current Corona Discharges in Dry Air Fed Coaxial Wire-cylinder Reactors. *Journal of Applied Physics*. 113(18), 183301-1 to 183301-10.
- Yehia, A. (2007). Calculation of Ozone Generation by Positive DC Corona Discharge in Coaxial Wirecylinder Reactors. *Journal of Applied Physics*. 101(2), 023306-1 to 023306-5.
- Yehia, A., Mizuno, A. and El-Osealy, M. A. M. (2004). Calculation of Ozone Generation in AC Corona Discharge Reactor. *Japanese Journal of Applied Physics*. 43(8A), 5558–5561.

- Zhang, H., Liu, Z., Xu, D. and Wang, N. (2010). Soft-Sensor of Ozone Concentration in Ozone Generation System. *Ozone: Science & Engineering: The Journal of the International Ozone Association*. 32(1), 56–60.
- Zhu, S., Chen, Y., Zhang, G. and Sa, J. (2010). A Near-infrared Optical Fiber Sensor for Carbon Monoxide Concentration Monitoring. *Microwave and Optical Technology Letters*. 52(10), 2192–2195.