Theoretical analysis for ozone yield of a high frequency silent discharge

by Mochammad Facta

Theoretical analysis for ozone yield of a high frequency silent discharge

Cite as: AIP Conference Proceedings **1818**, 020073 (2017); https://doi.org/10.1063/1.4979940

Mochammad Facta, Hermawan, Z. Salam, Z. Buntat, and I. R. Smith

AIP Conference Proceedings **1818**, 020073 (2017); https://doi.org/10.1063/1.4979940 **1818**, 020073

Theoretical Analysis for Ozone Yield of a High Frequency Silent Discharge

Mochammad Facta[1, a)],Hermawan[1)], Z.Salam[2)], Z. Buntat[3)], and I.R. Smith[4)]

[1]*Electrical Engineering Department, Universitas Diponegoro (UNDIP), Indonesia*
[2]*Energy Conversion (Encon) Department, Universiti Teknologi Malaysia (UTM), Malaysia*
[3]*High Voltage and High Current Institute (IVAT), Universiti Teknologi Malaysia (UTM), Malaysia*
[4]*Department of Electronic and Electrical Engineering, Loughborough University, United Kingdom*

[a)]Corresponding author: facta@elektro.undip.ac.id; mochfacta@gmail.com

Abstract. The paper uses dimensional analysis to develop a theoretical prediction of the yield of a high frequency silent discharge ozone generator at atmospheric pressure. To verify the viability of the resulting yield equation, a rectangular shaped chamber with a 0.75 mm air gap was constructed. Aluminium mesh electrodes were used, with metal tape and a planar mica sheet forming a dielectric barrier. The power supply to the chamber was from a modified class E resonant power inverter. It is established that prediction using the yield equation based on fractional function matches closely with data obtained from the experimental findings.

INTRODUCTION

It has found that ozone gas is used in wide application in many water treatment, pharmaceutical and other applications [1, 2] as it leaves no harmful residuals in environment. The most economical method of ozone generation is a silent discharge [3,4] and this discharge has been investigated [5] with a view to improving the overall yield. Dimensional analysis [6] is a useful tool for predicting the oxygen yield from a given reaction chamber [7]. To use this, it is necessary to determine the significant parameters that influence the yield and then to properly formulate and weight these in a mathematical model. Useful models have been developed for ozone generation by pulse streamer discharge [7, 8], but to date no corresponding analysis has been reported for the high frequency silent discharge. The paper uses dimensional analysis to predict the ozone yield (in g/kWh) of a high frequency silent discharge. Results predicted from the analysis are compared with practical measurements.

EXPERIMENTAL, RESULTS AND DISCUSSION

Based on the evidences in the literatures, the most prominent in ozone yields parameters are: gas flow rate, power absorbed by the chamber, pressure, applied voltage, frequency, the permittivity of the dielectric medium and the discharge gap [1,8]. These parameters are grouped into four fundamental dimensional quantities: length (L), mass (M), time (T) and current (A) as summarized in Table 1.The general relationship between the ozone yield and the parameters in Table 1 can be written in the following equation [6]

$$(O_3) = function(f,\ V, P, d_g, f_r, P_s, \varepsilon) \qquad (1)$$

Engineering International Conference (EIC) 2016
AIP Conf. Proc. 1818, 020073-1–020073-4; doi: 10.1063/1.4979940
Published by AIP Publishing. 978-0-7354-1486-0/$30.00

TABLE 1. Parameters influence the ozone yield

Parameters	Symbol	Unit	Dimension
ozone yield	O_3	g/kWh	$L^{-2}M^{2}$
frequency	f	Herzt (Hz)	T^{-1}
voltage	V	Volt (V)	$L^{2}MT^{-3}A^{-1}$
power	P	Watt (W)	$L^{2}M^{1}T^{-3}$
discharge gap	d_g	Meter (M)	L^{1}
permittivity of dielectric	ε	F/m	$L^{-3}M^{-1}T^{2}A^{4}$
flow rate	f_r	Litre/minute (L/m)	$L^{3}T^{-1}$
pressure	P_s	Pascal (Pa)	$L^{-1}MT^{-2}$

By following the steps in Buckingham's Theorem [6], these eight parameters are expressed in terms of fundamental dimensions as shown in the first four rows of the dimensional matrix in Equation (1). The determinants of the first four rows and the last four columns of the matrix are non-zeros with rank four. The number of dimensionless products (π) that characterize the system is only four: π_1, π_2, π_3,π_4.

$$\begin{array}{c|cccc|cccc} & O_3 & f & V & P & d_g & f_r & P_s & \varepsilon \\ \hline L & -2 & 0 & 3 & 2 & 1 & 2 & -1 & -3 \\ M & 0 & 0 & 0 & 1 & 0 & 1 & 1 & -1 \\ T & 2 & -1 & -1 & -3 & 0 & -3 & -2 & 4 \\ A & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 2 \\ \hline \pi_1 & 1 & 0 & 0 & 0 & & & & \\ \pi_2 & 0 & 1 & 0 & 0 & & & & \\ \pi_3 & 0 & 0 & 1 & 0 & & & C & \\ \pi_4 & 0 & 0 & 0 & 1 & & & & \end{array} \qquad (2)$$

whereas C is determined by $C= -D(A^{-1}.\ B)^{T}$ [6] (3)
in which

$$A=\begin{bmatrix} -1 & 2 & -1 & -3 \\ 0 & 1 & 1 & -1 \\ 0 & 3 & -2 & -4 \\ 0 & -1 & 0 & 2 \end{bmatrix},\ B=\begin{bmatrix} -2 & 0 & 3 & 2 \\ 0 & 0 & 0 & 1 \\ 2 & -1 & -1 & -3 \\ 0 & 0 & 0 & 0 \end{bmatrix}, D=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, C=\begin{bmatrix} -4 & 2 & 0 & 0 \\ 3 & -1 & 0 & 0 \\ -1 & 0 & -\frac{1}{2} & \frac{1}{2} \\ 0 & -1 & -1 & 0 \end{bmatrix}$$

When the result follow equation (1) and (2) then value of C is in (1) yields:

$$\begin{array}{c|cccc|cccc} & O_3 & f & V & P & d_g & f_r & P_s & \varepsilon \\ \hline L & -2 & 0 & 3 & 2 & 1 & 2 & -1 & -3 \\ M & 0 & 0 & 0 & 1 & 0 & 1 & 1 & -1 \\ T & 2 & -1 & -1 & -3 & 0 & -3 & -2 & 4 \\ A & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 2 \\ \hline \pi_1 & 1 & 0 & 0 & 0 & 4 & 2 & 0 & 0 \\ \pi_2 & 0 & 1 & 0 & 0 & 3 & -1 & 0 & 0 \\ \pi_3 & 0 & 0 & 1 & 0 & -1 & 0 & -\frac{1}{2} & \frac{1}{2} \\ \pi_4 & 0 & 0 & 0 & 1 & 0 & -1 & -1 & 0 \end{array} \qquad (4)$$

From matrix in equation (3) the set of dimensionless product is:

$$\pi_1 = O_3 f_r^2 d_g^4\,;\ \pi_2 = f\,\frac{d_g^3}{f_r}\,;\ \pi_3 = \frac{V\varepsilon^{\frac{1}{2}}}{P_s^{\frac{1}{2}} d_g}\,;\ \pi_4 = \frac{P}{f_r P_s} \qquad (5)$$

Buckingham's theorem states [6] that the dimensionless products can be related among themselves by

$$\pi_1 = function\left(\pi_2, \pi_3, \pi_4\right) \qquad (6)$$

This leads to the following expression: $\pi_1 = D_c \pi_2^{m_2}\ \pi_3^{m_3} \pi_4^{m_4}$ (7)

Equation (7) is known as monomial form, which is defined as a product of several variables with powers. The variable D_c is a dimensional constant, and m_2 *to* m_4 are the powers of each dimensionless product to be determined later. Introducing set of Equations (5) into (7) enables:

$$(O_3) = D_c\left(\frac{d_g^4}{f_r}\right)\left(\frac{d_g^3 f}{f_r}\right)^{m_2}\left(\frac{V\varepsilon^{\frac{1}{2}}}{P_s^{\frac{1}{2}}d_g}\right)^{m_3}\left(\frac{P}{f_r P_s}\right)^{m_4} \tag{8}$$

By considering the physical phenomena in [1, 5, 9] and employing a trial and error method, the values of m_2, m_3, m_4 are determined to be $-\frac{3}{2}$, +3 and –1, respectively. The Equation (8) becomes

$$(O_3) = D_c\left(\frac{V^3\varepsilon^{\frac{3}{2}}\sqrt{f_r}}{f^{\frac{3}{2}}d_g^{\frac{7}{2}}P\sqrt{P_s}}\right) \quad \text{and} \quad K = \left(\frac{\varepsilon^{\frac{3}{2}}\sqrt{f_r}}{f^{\frac{3}{2}}d_g^{\frac{7}{2}}\sqrt{P_s}}\right) \tag{9}$$

Since ε, f_r, f, d_g, and P_s are held constant throughout the implementation of V and P, it is convenient to write

$$D_c = \frac{(O_3)}{K\left(\frac{V^3}{P}\right)} \tag{10}$$

Fig. 1 shows the experimental set up to accomplish mathematical model. The discharge chamber is constructed by rectangular shaped aluminium electrodes and metal tape [9]. A modified class E high frequency resonant inverter is used as power supply to generate high voltage. The ozone yield is measured at the following conditions: flow rate =1.0 L/m, discharge gap width =0.75 mm, frequency =27.5 kHz, pressure =1.01325 x 10^5 Pa and Voltage varied from 2.0 – 4.0 kV_{pp}. As D_c is set to 1.5, then the plot of Equation (10) fits well with experimental data for voltages below the saturation region in Fig. 2. However, the theoretical curve does not accommodate the points beyond the saturated region in which the collisions of electron and ozone molecules become more intensive due to excessive energy. This reaction results in reduced ozone production and they are accommodated by Destruction Factor (*DF*) in the form of:

$$DF = \frac{(O_3)}{D_c K\left(\frac{V^3}{P}\right)} \tag{11}$$

The initial voltage (V_o) and power (P_o) also must consider as $\left({}^{VP}\!/_{V_oP_o}\right)$. Three regression methods, namely the quadratic, third order polynomial, and fractional function, Curve Expert software is used to fit the data points to the curves. From Fig. 3, the fractional function results the best coefficient of determination (R^2). Note that if R^2 is unity, the regression curve fits perfectly to the *DF* data strand. The recommended the equation for DF based on fractional function :

$$D_F = \frac{-0.29 + 0.37\left(\frac{VP}{V_oP_o}\right)}{\left[1 - 0.13\left(\frac{VP}{V_oP_o}\right) + 0.0048\left(\frac{VP}{V_oP_o}\right)^2\right]} \tag{12}$$

Finally, by combining Equation (11) with (12), the equation to predict the ozone yield can be written as:

$$(O_3) = (1.5)\left(\frac{V^3\varepsilon^{\frac{3}{2}}\sqrt{f_r}}{f^{\frac{3}{2}}d_g^{\frac{7}{2}}P\sqrt{P_s}}\right)\left(\frac{-0.29 + 0.24\left(\frac{VP}{V_oP_o}\right)}{\left[1 - 0.13\left(\frac{VP}{V_oP_o}\right) + 0.0048\left(\frac{VP}{V_oP_o}\right)^2\right]}\right) \tag{13}$$

In Fig. 4, the prediction curves successfully accommodate the initiation condition at the beginning of the ozone yield at different flow rates i.e. 0.5 and 1.0 L/m by incorporating the *DF* in the equation.

CONCLUSION

1. The paper has demonstrated the use of dimensional analysis in predicting the yield for a high frequency silent discharge ozone generator.
2. An experimental unit is constructed and it is found that good agreement is obtained between theoretically predicted results and those obtained experimentally.
3. The prediction curves successfully adobe the ozone yield at different flow rate with coefficient of determination (R^2) closes to unity.

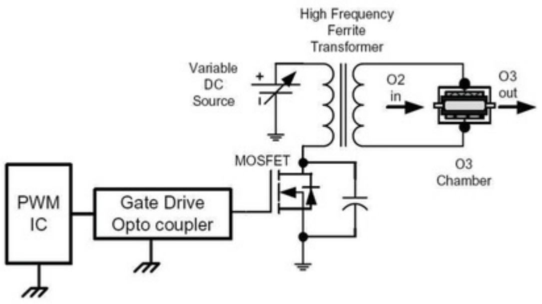

FIGURE 1. Experimental Set Up

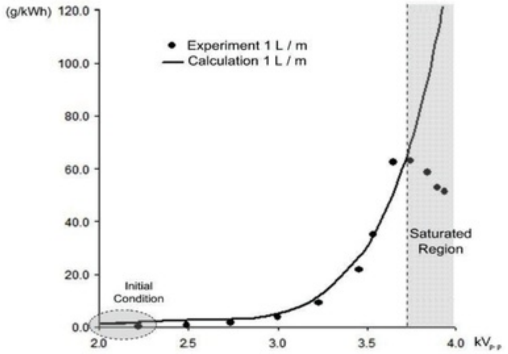

FIGURE 2. Measured and calculated ozone yield

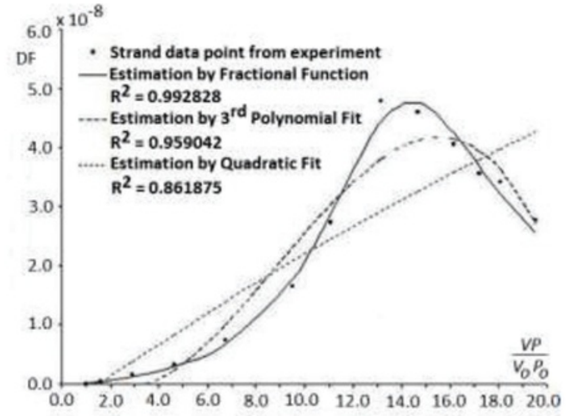

FIGURE 3. *DF* for ozone yield

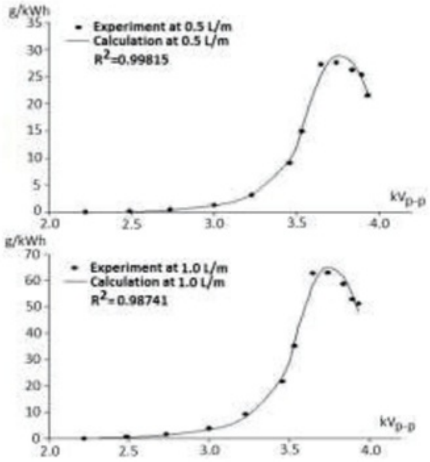

FIGURE 4. Ozone yield at 0.5 L/m and 1.0 L/m

REFERENCES

1. U. Kogelschatz, B. Eliasson, *Ozone Generation and Application in Handbook of Electrostatic Processes* (Marcel Dekker, 1995), pp. 581 – 605.
2. M. Facta, Z. Salam, Z. Buntat, A. Yuniarto, “Silent Discharge Ozonizer for Colour Removal of Treated Palm Oil Mill Effluent Using A Simple High Frequency Resonant Power Converter” in Proceeding PECON 2010, pp. 39 – 44
3. A. Bogaerts, E. Neyts, R. Gijbels, J.V.D. Mullen, *Gas Discharge Plasma and Their Application*, Spectrochimica Acta Part B **57,** pp. 609 – 658 (2002)
4. M. Facta, Hermawan, N. A. K. Umiati, Z. Salam, and Z. Buntat, "Implementation of photovoltaic and simple resonant power converter for high frequency discharge application," in Proceeding ICITACEE 2015, pp. 193-196.
5. Z. Buntat, I.R. Smith, N.A.M. Razali, *Ozone Generation by Pulsed Streamer Discharge in Air*, Applied Physics Research **1,** pp. 2 – 10 (2009)
6. T.Szirtes, *Applied Dimensional Analysis and Modeling* (McGraw-Hill, 1997)
7. Z. Buntat, J. E. Harry, I.R. Smith, *Application of Dimensional Analysis to Ozone Production by Pulsed Streamer Discharge in Oxygen*, J. Phys. D: Appl. Phys., pp. 1553-1557 (2003).
8. Z. Buntat , I.R. Smith, dan N.A.M. Razali, *Ozone Generation Using Atmospheric Pressure Glow Discharge in Air*, J. Phys. D: Appl. Phys. **42**, pp. 1 – 5 (2009)
9. M. Facta, Z. Salam, Z. Buntat, *A New Type of Planar Chamber for High Frequency Ozone Generator System*, Advanced Materials Research **896**, pp. 726 – 729 (2014)

Theoretical analysis for ozone yield of a high frequency silent discharge

ORIGINALITY REPORT

14%	%	14%	%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Nikolay Hinov, Gergana Vacheva, Zoran Zlatev. "Modelling a charging process of a supercapacitor in MATLAB/Simulink for electric vehicles", AIP Publishing, 2018 Publication	4%
2	N.A. Roslan, Z. Buntat, M.A.B. Sidik. "Application of dimensional analysis for prediction of NOx removal", 2013 IEEE 7th International Power Engineering and Optimization Conference (PEOCO), 2013 Publication	2%
3	Henny Pratiwi Adi. "Technical skills requirement of Indonesian construction labors to work in Malaysia", AIP Publishing, 2017 Publication	2%
4	Facta, Mochammad, Z. Salam, and Z. Buntat. "A New Type of Planar Chamber for High Frequency Ozone Generator System", Advanced Materials Research, 2014. Publication	2%

5	Dedy K. Setiawan, Rina Anggraeni. "Analysis of input-output characteristic and generation cost optimization using quadratic least square regression and dynamic genetic algorithm method: Case study PT.PLN PJB UP Gresik", AIP Publishing, 2017 Publication	2%
6	A Yahya. "Determination of material removal rate of an electro-discharge machine using dimensional analysis", Journal of Physics D Applied Physics, 05/21/2004 Publication	1%
7	Mochammad Facta, Hermawan, Ngurah Ayu Ketut Umiati, Zainal Salam, Zolkafle Buntat. "Implementation of photovoltaic and simple resonant power converter for high frequency discharge application", 2015 2nd International Conference on Information Technology, Computer, and Electrical Engineering (ICITACEE), 2015 Publication	1%
8	Yahya, Azli, Trias Andromeda, Ade Erawan Minhat, Nor Hisham Khamis, Kamal Kalil, and Muhammad Arif Abdul Rahim. "Comparison Studies of Electrical Discharge Machining (EDM) Process Model for Low Gap Current", Advanced Materials Research, 2012. Publication	1%

9	Mochammad Facta, Hermawan, Zainal Salam, Zolkafle Buntat. "Piezoelectric transformer with pulse dropping technique for high voltage generation", 2016 2nd International Conference of Industrial, Mechanical, Electrical, and Chemical Engineering (ICIMECE), 2016 Publication	1 %
10	Mochammad Facta, Hermawan, Karnoto, Zainal Salam, Zolkafle Buntat. "Double dielectric barrier discharge chamber for ozone generation", 2014 The 1st International Conference on Information Technology, Computer, and Electrical Engineering, 2014 Publication	<1 %

Exclude quotes	Off	Exclude matches	Off
Exclude bibliography	On		